INTERIM GEOLOGIC MAP OF THE PANGUITCH 30' X 60' QUADRANGLE, GARFIELD, IRON, AND KANE COUNTIES, UTAH

by

Robert F. Biek[1], Peter D. Rowley[2], John J. Anderson[3], Florian Maldonado[4], David W. Moore[4], Jeffrey G. Eaton[5], Richard Hereford[4], and Basia Matyjasik[1]

[1] Utah Geological Survey, P.O. Box 146100, Salt Lake City, UT 84114-6100
[2] Geologic Mapping Inc., P.O. Box 651, New Harmony, UT 84757
[3] Kent State University, retired
[4] U.S. Geological Survey, retired
[5]Department of Geosciences, Weber State University, Ogden, UT 84408-2507

Disclaimer

This open-file release makes information available to the public during the review and production period necessary for a formal UGS publication. The map may be incomplete, and inconsistencies, errors, and omissions have not been resolved. While the document is in the review process, it may not conform to UGS standards; therefore, it may be premature for an individual or group to take actions based on its contents.

Although this product represents the work of professional scientists, the Utah Department of Natural Resources, Utah Geological Survey, makes no warranty, expressed or implied, regarding its suitability for a particular use. The Utah Department of Natural Resources, Utah Geological Survey, shall not be liable under any circumstances for any direct, indirect, special, incidental, or consequential damages with respect to claims by users of this product. For use at 1:65,000 scale only.

This geologic map was funded by the Utah Geological Survey and the U.S. Geological Survey, National Cooperative Geologic Mapping Program through USGS STATEMAP award numbers 08HQAG0096, G09AC00152, G10AC00386, and G11AC20249. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

UTAH DNR GEOLOGICAL SURVEY

OPEN-FILE REPORT 599
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
in cooperation with the U.S. Geological Survey
2012

MAP UNIT DESCRIPTIONS

QUATERNARY

Artificial deposits

Qf **Artificial fill** (Historical) − Engineered fill used to construct the dam at Navajo Lake; fill of variable thickness and composition should be anticipated in all developed or disturbed areas; typically less than 20 feet (6 m) thick.

Qfd **Disturbed land** (Historical) – Disturbed area in Castle Valley (about 5 miles [9 km] southwest of Panguitch Lake) mapped because it obscures extent of glacial deposits and landforms; also includes large sand and gravel pits southeast of Panguitch and northwest of Bryce Canyon.

Alluvial deposits

Qal **Stream alluvium** (Holocene) − Moderately sorted sand, silt, clay, and pebble to boulder gravel deposited in active, main stem stream channels and floodplains of the Sevier River and its few well-graded major tributaries; locally includes minor stream-terrace alluvium as much as about 10 feet (3 m) above current base level; inferred to overlie older alluvial and fan deposits in the valley of the Sevier River; probably less than 30 feet (<9 m) thick.

Qat **Stream-terrace alluvium** (Holocene to middle? Pleistocene) − Moderately sorted sand, silt, and pebble to boulder gravel that forms incised gently sloping terraces above the Sevier River and its few well-graded major tributaries; deposited in stream-channel environment, but locally includes colluvium and small alluvial fans; terraces are at elevations of about 10 to 120 feet (3–35 m) above adjacent streams, but are not subdivided here due to limitations of map scale; typically less than 20 feet (<6 m) thick.

Qaly **Young stream alluvium** (Holocene) − Similar to stream alluvium (Qal) and the youngest (lowest elevation) part of stream-terrace alluvium (Qat), but undivided here due to limitations of map scale; this combined unit is commonly mapped in upland drainages where it may include small alluvial-fan deposits from tributary drainages and colluvium from adjacent slopes; commonly grades downslope into alluvial fans; locally includes historical debris-flow and debris-flood deposits derived from tributary drainages, as, for example, the deposits of the 1995 Black Mountain debris flow that entered the upper reaches of Coal Creek in Cedar Canyon (Giraud and Lund, 2006); typically less than 20 feet (<6 m) thick, but deposits of major stream valleys may locally exceed 30 feet (9 m) thick.

Qalo **Old stream alluvium** (Holocene and upper Pleistocene) – Similar to lower- to middle-elevation parts of stream-terrace alluvium (Qat), but these dissected deposits are largely restricted to upland drainages not well graded to the Sevier River; typically less than 20 feet (<6 m) thick.

Qao **Oldest stream alluvium** (Pleistocene) – Moderately sorted sand, silt, and pebble to boulder gravel that forms topographically inverted channel deposits at the mouth of Clear Creek and on the south side of Panguitch Lake, both in the Panguitch Lake 7.5' quadrangle; the latter deposits were well exposed near Panguitch Lake in excavations associated with a new housing development that revealed interbedded sand and pebbly to cobbly, locally iron-stained gravel containing clasts mostly of the Isom Formation (Ti, which is commonly grussy weathering) and subordinate chalcedony and quartzite, but apparently lacking basalt; unit includes deposits that underlie the nearby Cooper Knoll lava flow and that consist of subrounded to rounded pebbles to boulders of the Isom Formation, mafic volcanic rocks, chalcedony, and, especially near the base of the deposits, quartzite pebbles and cobbles; the source of the quartzite pebbles and cobbles is unknown, but they are doubtless ultimately recycled from the Grand Castle Formation (redefined), or Drip Tank Member of the Straight Cliffs Formation now exposed in grabens below the western rim of the Markagunt Plateau; these deposits record an early phase in the development of the Clear Creek–Rock Canyon drainage, the lower part of which is now drained by the markedly underfit Pass Creek; deposits near Panguitch Lake are 40 to 60 feet (12–18 m) thick, and those underlying the Cooper Knoll lava flow are as much as 120 feet (35 m) thick.

Qam **Marsh alluvium** (Holocene and upper Pleistocene) − Dark-yellowish-brown clay, silt, sand, and minor gravel lenses deposited in closed depressions on landslides and glacial moraines in the Lowder Creek area east of Brian Head peak; forms small marshy areas characterized by cattails and other hydrophilic vegetation; typically less than 10 feet (3 m) thick, but marsh alluvium of Lowder Creek bog, described in more detail under the unit description for “glacial till of Pinedale age,” is at least 21 feet (7 m) thick (Mulvey and others, 1984).

Qap **Pediment alluvium** (Holocene and Pleistocene) – Poorly sorted sand and gravel containing subangular to rounded clasts that forms a locally resistant cap on eroded bedrock surfaces or, locally, on old fan alluvium (Taf); represents multiple surfaces from several tens of feet to more than 100 feet (30 m) above modern drainages; deposited principally as debris flows, debris floods, and in ephemeral stream channels; typically less than 20 feet (<6 m) thick.

Qaf_1 **Young fan alluvium** (Holocene) − Poorly to moderately sorted, non-stratified, clay- to boulder-size sediment containing subangular to subrounded clasts deposited principally by debris flows and debris floods at the mouths of active drainages; equivalent to the upper part of younger fan alluvium (Qafy), but differentiated because Qaf_1 typically forms smaller, isolated fans; probably less than 30 feet (<9 m) thick.

Qaf_2 **Middle fan alluvium** (Holocene and upper Pleistocene) − Similar in composition and morphology to young fan alluvium (Qaf_1), but forms inactive surfaces incised by younger stream and fan deposits; equivalent to the older, lower part of young and middle fan alluvium (Qafy) and coalesced fan alluvium of Parowan Valley

(Qafc); these deposits preserve previously unreported fault scarps east and north of Summit in southern Parowan Valley that appear to be the southwest continuation of the Parowan Valley faults that Williams and Maldonado (1995) and Black and Hecker (1999) inferred to be latest Pleistocene to early Holocene in age; probably less than 30 feet (<9 m) thick.

Qafy **Young and middle fan alluvium, undivided** (Holocene and upper Pleistocene) − Poorly to moderately sorted, non-stratified, boulder- to clay-size sediment containing subangular to subrounded clasts deposited at the mouths of streams and washes; forms both active depositional surfaces (Qaf_1 equivalent) and low-level inactive surfaces incised by small streams (Qaf_2 equivalent) that are undivided here; deposited principally as debris flows and debris floods, but colluvium locally constitutes a significant part; small, isolated deposits are typically less than a few tens of feet thick, but large, coalesced deposits in Sevier and Parowan Valleys are much thicker and form the upper part of basin-fill deposits.

Qafc **Coalesced fan alluvium of Parowan Valley** (Holocene and Pleistocene) – Similar to young and middle fan alluvium (Qafy) but forms large, coalesced fans of Parowan Valley; typically exhibits a lower overall slope than young and middle fan alluvium, which we mapped as smaller fans close to the range front; forms unfaulted, active surfaces deposited principally as debris flows and debris floods; thin planar beds with small snails exposed in arroyo walls immediately east of Winn Gap (at the south end of the Red Hills) may represent deposits of a shallow lake or playa (Biek and others, in preparation), but it is unclear what may have blocked the outlet at Winn Gap (alternatively, these deposits may simply be distal fan alluvium); thickness uncertain, but Hurlow (2002) showed that Quaternary and Neogene basin fill is in excess of 2000 feet (600 m) thick in southern Parowan Valley west of Parowan and that this basin fill thickens to the northeast; only the uppermost part of this basin-fill is included in map unit Qafc, which we assume to be in excess of several tens of feet thick.

Qafo **Older fan alluvium** (Pleistocene) – Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder- to clay-size sediment with moderately developed calcic soils (caliche); forms broad, gently sloping, incised surfaces in Parowan Valley and Sevier valley; fault scarps locally prominent on these deposits; deposited principally as debris flows and debris floods; exposed thickness as much as several tens of feet.

Qaf **Oldest fan alluvium** (Pleistocene) – Similar in composition to older fan alluvium, but forms deeply dissected surfaces with little or no remaining fan morphology; preserved in the footwall of inferred faults in southern Sevier valley; also includes deposits that enclose the 1.0 Ma Summit lava flow and overlie the 1.3 Ma Red Hills lava flow at the south end of the Red Hills; maximum exposed thickness is about 150 feet (45 m).

Colluvial deposits

Qc **Colluvium** (Holocene and upper Pleistocene) − Poorly to moderately sorted, angular, clay- to boulder-size, locally derived sediment deposited by slope wash and soil creep on moderate slopes and in shallow depressions; locally grades downslope into deposits of mixed alluvial and colluvial origin; mapped only where it conceals contacts or fills broad depressions; the Claron and Brian Head Formations and Upper Cretaceous strata shed enormous amounts of colluvium, such that an apron of heavily vegetated colluvium (unmapped because it forms a veneer having poor geomorphic expression) typically envelops at least the lower part of steep slopes along their outcrop belt; typically less than 20 feet (6 m) thick.

Qco **Older colluvium** (upper Pleistocene) – Similar to colluviums but deeply incised by modern drainages on the flanks of the Sevier and Paunsaugunt Plateaus; typically less than 40 feet (12 m) thick.

Eolian deposits

Qed **Eolian dune sand** (Holocene) − Grayish-pink to pale-red, well-sorted silt and fine-grained sand largely stabilized by vegetation on the Cedar Breaks escarpment; most of the sand consists of tiny clay pellets eroded from the Claron Formation and carried eastward up the scarp by strong winds; typically less than 15 feet (5 m) thick.

Qes **Eolian sand** (Holocene) − Yellowish-brown to reddish-brown, moderately well sorted sand and silt derived from deflation of Little Salt Lake playa deposits located to the south and west; forms thin sheets and poorly developed dunes partly covered by sparse vegetation; generally more saline than underlying alluvium and so allows greasewood to flourish at the expense of sagebrush (Maldonado and Williams, 1993b); typically less than 6 feet (2 m) thick.

Lacustrine and playa deposits

Qlg **Coarse-grained lacustrine sediment** (Holocene and upper Pleistocene) – Sand and gravel deposited at the east end of Navajo Lake, which formed behind a lava dam created by the Henrie Knolls lava flows; probably 10 to 15 feet (3–5 m) thick.

Qlp **Little Salt Lake playa deposits** (Holocene) – Calcareous, saline, and gypsiferous gray clay, silt, and fine-grained sand deposited on the flat playa floor of Little Salt Lake in the southwest part of Parowan Valley; locally includes small dunes of eolian silt; at least 25 feet (8 m) thick.

The Little Salt Lake playa formed in response to relative uplift of the Red Hills structural block (Threet, 1952; Maldonado and Williams, 1993a, b). The playa reflects ponded drainage and represents the latest stage in the history of antecedent drainage through Parowan Gap (Maldonado and Williams, 1993b). We infer that a playa has occupied this area intermittently throughout the Pleistocene, but deposits at and near the surface are doubtless Holocene in age.

Qlm **Little Salt Lake playa-margin deposits** (Holocene and upper Pleistocene) – Calcareous, saline, and gypsiferous gray clay, silt, sand, and local volcanic and quartzite pebbles, deposited on gentle slopes around the margin of Little Salt Lake playa; periodically flooded during high lake levels; includes small alluvial fans, eolian sand and silt, and alluvium; less than 12 feet (4 m) thick.

Mass-movement deposits

Qms, Qmsh, Qms?, Qms(Kd), Qms(Ti), Qms(Tql), Qms(Tm)

Landslides (Historical? and upper? Pleistocene) − Very poorly sorted, locally derived material deposited by rotational and translational movement; composed of clay- to boulder-size debris as well as large, partly intact, bedrock blocks; characterized by hummocky topography, numerous internal scarps, chaotic bedding attitudes, and common small ponds, marshy depressions, and meadows; the largest landslide complexes involve tuffaceous strata of the Brian Head (Tbhv) and Dakota (Kd and Ktd) Formations, and to a lesser extent the Limerock Canyon Formation (Tl), and are several square miles in size; Qmsh denotes landslides known to be active in historical time, but any landslide deposit may have been historically active even if not so identified; large rotational slump blocks of Isom Formation (Qms[Ti]) and Leach Canyon Formation (Qms[Tql]) are mapped in the Yankee Meadows graben and in the lower part of the Lowder Creek basin, and slump blocks of Dakota Formation (Qms[Kd]) are mapped in Cedar Canyon; Qms(Tm) represents landslide debris of the Markagunt Megabreccia present northwest of Cedar Breaks National Monument; query indicates areas of unusual morphology that may be due to landsliding; thickness highly variable, but typically several tens of feet or more thick and the largest landslides, at Yankee Meadows graben, may be as much as 600 feet (200 m) thick (Maldonado and others, 1997).

Undivided as to inferred age because new research shows that even landslides having subdued morphology (suggesting that they are older, weathered, and have not experienced recent large-scale movement) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003).

The most active and problematic landslide in the map area is in Cedar Canyon where State Highway 14 crosses the upper part of the Dakota Formation. Lund and others (2009) reported on a large rock fall associated with this landslide that closed the highway for 6 days in January 2009. The landslide moved again on October 8, 2011, destroying the road and closing the highway for nearly a year.

Dense forests and widespread colluvium may conceal unmapped landslides, and more detailed imaging techniques such as LiDAR may show that many slopes, particularly those developed on the Brian Head (Tbhv) and Bear Valley (Tbv) Formations and on Upper Cretaceous strata, host surficial deposits that reveal evidence of creep or shallow landsliding. Understanding the location, age, and stability of landslides, and of slopes that may host as-yet unrecognized landslides, requires detailed geotechnical investigations.

Qmt **Talus** (Holocene and upper Pleistocene) − Poorly sorted, angular cobbles and boulders and finer-grained interstitial sediment deposited principally by rock fall on or at the base of steep slopes; talus that is part of large landslide complexes is not mapped separately; talus is common at the base of steep slopes across the map area, but is only mapped where it conceals contacts or forms broad aprons below cliffs of resistant bedrock units; commonly grades downslope into colluvium; typically less than 30 feet (9 m) thick.

Mixed-environment deposits

Qac **Alluvium and colluvium** (Holocene and upper Pleistocene) − Poorly to moderately sorted, generally poorly stratified, clay- to boulder-size, locally derived sediment deposited in swales and small drainages by fluvial, slope-wash, and creep processes; generally less than 20 feet (6 m) thick.

Qaco **Older alluvium and colluvium** (upper Pleistocene?) − Similar to mixed alluvium and colluvium (Qac), but forms incised, isolated remnants, typically in the upper reaches of streams; probably about 20 to 30 feet (6–9 m) thick.

Qacf **Alluvium, colluvium and fan alluvium** (Holocene and upper Pleistocene?) − Poorly to moderately sorted, non-stratified, clay- to boulder-size sediment deposited principally by debris flows, debris floods, and slope wash at the mouths of active drainages and the base of steep slopes; locally reworked by small, ephemeral streams; forms coalesced apron of fan alluvium and colluvium impractical to map separately at this scale; typically 10 to 40 feet (3–12 m) thick.

Also mapped in sediment-choked drainages that drain the Paunsaugunt and Sevier Plateaus, where it consists of modern alluvium, low-level terrace alluvium, colluvium, and fan alluvium impractical to differentiate at the map scale. The upper reaches of these deposits are typically characterized by debris-flow deposits partly reworked by braided channels, probably a result of flashflood runoff on the Claron Formation. The morphology of many of these drainages suggests that they are partly backfilled following an earlier, deeper level of canyon erosion, and in the larger drainages, these deposits are likely several tens of feet thick.

Qacfo **Older colluvium and fan alluvium** (Pleistocene) − Mapped below the west edge of the Markagunt Plateau, where it consists of poorly sorted, boulder- to clay-size sediment mostly derived from the Claron, Brian Head, and Isom Formations, and locally below the rim of the Paunsaugunt Plateau where it consists principally of reworked Claron debris; deposited principally by debris flows, debris floods, and slope wash; typically forms a resistant cap on isolated hill tops and ridges underlain by Upper Cretaceous strata, remnants of a once larger apron of sediment shed off the plateaus and now preserved as deeply dissected inverted valleys; also forms broad bench, preserved in the Iron Peak graben, west of the town of Brian Head, where it is locally exposed in the main scarp of a large landslide complex southeast of Sugarloaf Mountain (SE1/4SW1/4 section 8, T. 36 S., R. 9 W.); also forms incised, isolated remnants south of Haycock Mountain, in the upper reaches of the Clear Creek drainage, and a single deposit southeast of Brian Head peak; typically about 20 to 30 feet (6–9 m) thick but larger deposits may locally exceed 50 feet (15 m) thick.

Qae **Alluvium and eolian sand** (Holocene and upper Pleistocene) − Moderately to well sorted, mostly light-reddish-brown silt and sand deposited by sheetwash and ephemeral streams in small drainages and swales on the Henrie Knolls lava flow in the west-central part of the Henrie Knolls quadrangle; probably less than 10 feet (3 m) thick.

Qea **Eolian sand and alluvium** (Holocene and upper Pleistocene) − Moderately to well sorted, yellowish-brown sand deposited by wind and locally reworked by ephemeral streams; includes sand, silt, clay, and pebble to boulder gravel of stream channels; mapped in the southern Red Hills; probably less than 20 feet (6 m) thick.

Qaec **Alluvium, eolian sand, and colluvium** (Holocene and upper Pleistocene) − Moderately sorted, light-reddish-brown and moderate- to dark-yellowish-brown silt and sand and locally gravelly lenses deposited in swales and small drainages on and adjacent to the Henrie Knolls lava flow (Qbhk); the margins of the deposits include significant colluvium derived from adjacent hillslopes developed on the Claron Formation and basaltic lava flows; soils developed on this unit have an argillic horizon 1 to 1.5 feet (0.3–0.5 m) thick of moderate-reddish-brown sandy clay and clayey fine-grained sand; typically less than 10 feet (3 m) thick, although deposits in the Cow Lake area, south of the Henrie Knolls flows, are likely as much as 20 feet (6 m) thick.

Qca **Colluvium and alluvium** (Holocene to middle Pleistocene) − Poorly to moderately sorted, clay- to pebble-size, locally derived sediment deposited principally by slope wash and locally reworked by alluvial processes; typically mapped where lava flows dammed local washes causing ponding of mixed colluvial and alluvial sediment; distal, finer-grained parts form broad, open meadows; thickness uncertain, but likely less than about 20 feet (6 m) thick.

Qce **Colluvium and eolian sand** (Holocene to upper Pleistocene) − Poorly to moderately sorted, clay- to boulder-size, locally derived sediment—partly covered by a veneer of eolian sand—deposited by slope wash on moderate slopes and in shallow depressions in the Red Hills graben south of Parowan Gap and on the Red Canyon lava flow at the east margin of the valley of the Sevier River; colluvial debris is derived from adjacent lava flows and, in the Red Hills area, from the Navajo Sandstone; deposits in the Red Hills are probably less than 20 feet (6 m) thick; those near Red Canyon are probably less than about 6 feet (2 m) thick.

Qmtc **Talus and colluvium** (Holocene and upper Pleistocene) – Poorly sorted, angular to subangular, cobble- to boulder-size and finer-grained interstitial sediment deposited principally by rock fall and slope wash on steep slopes throughout the quadrangle; includes minor alluvial sediment at the bottom of washes; generally less than 30 feet (9 m) thick.

Qmtco **Older talus and colluvium** (upper Pleistocene) – Similar to talus and colluvium but deeply incised by modern drainages where it is mapped at the south end of the Sevier Plateau; generally less than 30 feet (9 m) thick.

Qmsc **Landslides and colluvium** (Holocene and upper Pleistocene) – Landslides and colluvium impractical to differentiate at this scale; as much as several tens of feet thick.

Qmsco **Older landslides and colluvium** (upper Pleistocene) – Older landslides and colluvium deeply incised by modern drainages on the west flank of the Sevier Plateau, about 1.5 miles (3 km) southeast of Blind Spring Mountain; as much as several tens of feet thick.

Qla **Lacustrine sediment and alluvium** (Holocene) − Forms the meadow of Blue Spring Valley about 2 miles (3 km) southwest of Panguitch Lake, which we interpret to be a lake deposit made up of moderately to well-sorted, thinly bedded, light-gray and light-brown, fine-grained sand, silt, and clay derived principally from Brian Head strata in the Bunker and Deer Creek drainages; upper surface is marked by numerous small stream channels and meander cutoffs; also mapped near the east end of Navajo Lake, where it consists of fine-grained sediment eroded from the pink member of the Claron Formation, and at Co-op Valley Sinks east of Parowan.

Blue Spring Valley was flooded to form a shallow reservoir following completion of the Blue Spring Valley dam in the late 1800s or early 1900s; the small dam was breached by 1917 (Ipson and Ipson, 2008). The valley is now drained at its north end by Spring Creek, which may have formed in response to the Miller Knoll lava flows that blocked the original outlet at the southeast end of the valley possibly as late as middle Holocene time. Lacustrine sediment and alluvium is likely several tens of feet thick in Blue Spring Valley, and may overlie stream deposits of ancestral Bunker Creek, which may have exited the southeast side of the valley prior to being blocked by the Miller Knoll lava flows.

Qlao **Older lacustrine sediment and alluvium** (Holocene and upper Pleistocene) − Similar to lacustrine sediment and alluvium (Qla), but forms incised, planar surfaces 5 to 10 feet (2–3 m) above the main meadow of Blue Spring Valley; likely several tens of feet thick.

Stacked unit deposits

Stacked unit deposits comprise a discontinuous veneer of Quaternary deposits that mostly conceal underlying bedrock units. Although most bedrock in the quadrangle is partly covered by colluvium or other surficial deposits, we use stacked units to indicate those areas where bedrock is almost wholly obscured by surficial deposits that are derived from more than just residual weathering of underlying bedrock.

Qlao/$Qbmk_3$

Older lacustrine sediment and alluvium over the Miller Knoll lava flow (Holocene and upper Pleistocene/Holocene to upper Pleistocene) − Mapped along the southeast edge of Blue Spring Valley (about 2 miles [3 km] southwest of Panguitch Lake) where the oldest Miller Knoll lava flow ($Qbmk_3$) is partly concealed by a veneer of sediment interpreted to be a mixture of lacustrine and alluvial, and possibly eolian, sand and silt; Blue Spring Valley likely drained through Black Rock Valley prior to being blocked by the Miller Knoll lava flows, with lacustrine and alluvial sediment accumulating in the basin upstream of the flows; surficial cover is likely less than 6 feet (2 m) thick.

Qc/Tbh

Colluvium over the Brian Head Formation (Holocene to Pleistocene/Oligocene to Eocene) – Mapped on the west flank of Houston Mountain (6 miles [10 km] east of Cedar Breaks National Monument) and south of the town of Brian Head, where colluvium, residual deposits, and possibly landslide deposits conceal the underlying Brian Head Formation; at Houston Mountain, colluvium includes large blocks of the Houston Mountain lava flow enclosed in a matrix of colluvium derived from weathered, tuffaceous Brian Head strata; also mapped on the flanks of the Sevier Plateau where colluvium derived mostly from the overlying Mount Dutton Formation obscures underlying Brian Head strata; surficial cover may exceed 20 feet (6 m) thick.

Qc/Tcwu

Colluvium over the upper limestone unit of the white member of the Claron Formation (Holocene and upper Pleistocene/Eocene) – Mapped on the southwest side of Houston Mountain (6 miles [10 km] east of Cedar Breaks National Monument) where colluvium conceals the underlying upper limestone unit of the white member of the Claron Formation; colluvium includes large blocks of the Houston Mountain lava flow enclosed in a matrix of colluvium derived from weathered, tuffaceous Brian Head strata and the upper limestone unit of the white member of the Claron Formation; surficial cover may exceed 10 feet (3 m) thick.

Qc/Tcw

Colluvium over the white member of the Claron Formation (Holocene and upper Pleistocene/Eocene) – Mapped southeast of the Town of Bryce where the contact between the pink and white members of the Claron Formation is poorly exposed; strata mapped there as the white member may be an unusual facies of the uppermost pink member; surficial cover may exceed 10 feet (3 m) thick.

Qc/Tcp

Colluvium over the pink member of the Claron Formation (Holocene and upper Pleistocene/Eocene) – Mapped on the Paunsaugunt Plateau where a veneer of colluvium mostly conceals underlying bedrock; surficial cover mostly less than about 10 feet (3 m) thick.

Qc/Kws

Colluvium over the Wahweap and Straight Cliffs Formations (Holocene and upper Pleistocene/Upper Cretaceous) – Mapped west of Johns Valley where a veneer of colluvium mostly conceals underlying bedrock; surficial cover mostly less than about 10 feet (3 m) thick.

Glacial deposits

Glacial till and outwash are present only east of Brian Head peak in the Castle Creek and Lowder Creek drainages and in the greater Castle Valley area. These deposits are of the Pinedale alpine glacial advance and an older glaciation of uncertain Quaternary age. Pinedale deposits in their type area in the Wind River Range of Wyoming are about 12 to 24 ka (Imbrie and others, 1984) (with glacial maxima about 16 to 23 ka based on cosmogenic ^{26}Al and ^{10}Be dating; Gosse and others, 1995), and are roughly coeval with the late Wisconsin glaciation, Last Glacial Maximum (LGM), and Marine Oxygen Isotope Stage 2 (MIS 2). Laabs and Carson (2005) reported that Early Wisconsin glacial moraines (MIS 3–4, about 59 to 71 ka; Imbrie and others, 1984) are not known in Utah; however, we report a new Optically Stimulated Luminescence (OSL) age of 49 ka for pre-Pinedale till exposed on the southeast margin of Castle Valley, and it may be that the MIS 3-4 advance is more widespread in the west than originally thought (Tammy Rittenour, Utah State University, written communication, August 3, 2010); it is also possible that this age is unreliable because the glacial till itself is derived from weathered felsic volcanic rocks. Deposits of the Bull Lake alpine glacial advance in their type area in the Wind River Range of Wyoming are about 128 to 186 ka (Imbrie and others, 1984) (with glacial maxima about 140 to 160 ka; Gosse and Phillips, 2001; Sharp and others, 2003), and are roughly coeval with the Illinoian glaciation or MIS 6.

Qgtp **Glacial till of Pinedale age** (upper Pleistocene) – Non-stratified, poorly sorted, sandy pebble to boulder gravel in a matrix of sand, silt, and minor clay; clasts are matrix supported, subangular to subrounded, and were derived from the Leach Canyon, Isom, and Brian Head Formations and the Markagunt Megabreccia exposed in the headwaters of the Castle Creek and Lowder Creek drainage basins; terminal moraine at the west end of Castle Valley is at an elevation of about 9750 feet (2973 m), whereas the terminal moraine of the smaller Lowder Creek basin is at Long Flat at an elevation of about 10,100 feet (3080 m); recessional and lateral moraines and hummocky, stagnant-ice topography are locally well developed, but sculpted bedrock is absent or inconspicuous, probably owing to the relatively small size and suspected short duration of the glaciers (Mulvey and others, 1984); well-developed terminal and recessional moraines are as much as 120 feet (37 m) thick, but till is much thinner elsewhere and locally consists only of scattered boulders or a veneer of meltout till on bedrock.

The Brian Head–Sidney Peaks area marks the southernmost occurrence of late Pleistocene glaciation in Utah (Mulvey and others, 1984), as first briefly described by Gregory (1950). Agenbroad and others (1996) interpreted glacial deposits and features that they attributed to their "Mammoth Summit glacier" at the southwest side of Brian Head peak and north edge of Cedar Breaks National Monument, but which we interpret as landslide deposits and in-place Brian Head

Formation, the latter partly covered by a lag of large blocks of the Isom Formation.

Till is Pinedale age based on distinct, well-preserved morainal morphology and relatively unweathered clasts, and a minimum limiting age of 14,400 ± 850 ^{14}C yr B.P. from marsh deposits of the Lowder Creek bog that overlies the till (Mulvey and others, 1984; Currey and others, 1986; see also Anderson and others, 1999). Madsen and others (2002) identified the 14,300 ^{14}C yr B.P. Wilson Creek #3 ash (erupted from Mono Craters in California) in the Lowder Creek bog. Marchetti and others (2005, 2007, 2011) and Weaver and others (2006) reported boulder exposure ages from four different moraines that indicate a local last glacial maximum of about 21.1 ka for the main Pinedale advance on Boulder Mountain approximately 80 miles (130 km) to the northeast. Their ages coincide with the global LGM (21 ± 2 ka) and thus likely are the age of the main Pinedale moraines on the Markagunt Plateau. Marchetti and others (2005, 2011) also reported a smaller advance at about 16 ka on Boulder Mountain.

Qgop **Glacial outwash of Pinedale age** (upper Pleistocene) – Moderately to well-sorted, generally subrounded, clast-supported, pebble to boulder sand and gravel; clasts are typically little weathered and of the same provenance as glacial till (Qgtp); mapped on the east side of Castle Valley where the deposits likely represent the waning stages of Pinedale glaciation; probably about 20 to 30 feet (6–9 m) thick.

Qgtu **Older glacial till of uncertain pre-Pinedale age** (middle? Pleistocene) – Similar to glacial till of Pinedale age, but glacial landforms are poorly preserved or absent; forms a low-relief, rubble-covered, locally hummocky surface both northeast and southwest of the southern Long Flat cinder cone (peak 10,392, north of lower Lowder Creek; map unit Qblfc); the northeast flank of this cinder cone is conspicuously truncated, perhaps by this glacial advance; also forms low hills south of Castle Valley, in the southwest part of the Panguitch Lake 7.5' quadrangle, that are composed almost entirely of large blocks of Leach Canyon Formation, with minor blocks of Isom Formation and chalcedony, that we infer to be the deeply eroded remains of a medial or recessional moraine; thickness uncertain, but probably about 10 to 30 feet (3–10 m) thick.

Mulvey and others (1984) and Currey and others (1986) first suggested that glacial till older than Pinedale age may be present in the Brian Head quadrangle, west of Castle Valley. We sampled a sandy till exposed in a bluff northwest of the confluence of Mammoth and Castle Creeks (map unit Qgtou) that yielded an OSL age of 48.95 ± 19.24 ka, suggesting that the deposits may correspond to the MIS 3-4 advance, but it is also possible that this age is unreliable because the glacial till itself is derived from weathered felsic volcanic rocks. Given the widespread extent and degree of incision of Qgtou deposits, we interpret these glacial deposits to be older, more likely of Bull Lake age.

Qgtou **Older glacial till and outwash, undivided** (upper to middle? Pleistocene) – Similar to older glacial till of uncertain pre-Pinedale age, but forms broad, open, boulder-strewn and sage-brush-covered, eastward-sloping surfaces of the Castle Creek and Mammoth Creek areas; exposures just north of the junction of Crystal Creek and Mammoth Creek suggest that most of this surface is underlain by till now deeply incised at its eastern end; glacial outwash deposits, especially those graded to the Pinedale terminal moraines, are presumed to be present locally on this till plain, but are not readily differentiated at this map scale; Mulvey and others (1984) and Currey and others (1986) briefly reported on possible ice wedge polygons as evidence for periglacial features on the southwest side of Castle Valley; glacial till is as much as 60 feet (18 m) thick where exposed near the confluence of Castle and Mammoth Creeks.

QUATERNARY-TERTIARY

Holocene(?) to upper Tertiary lava flows

Basaltic lava flows in the Panguitch 30' x 60' quadrangle are at the northern edge of the Western Grand Canyon basaltic field, which extends across the southwest part of the Colorado Plateau and adjacent High Plateaus transition zone with the Basin and Range Province in southwest Utah, northeast Arizona, and adjacent Nevada (Hamblin, 1963, 1970, 1987; Best and Brimhall, 1970, 1974; Best and others, 1980; Smith and others, 1999; Johnson and others, 2010). This volcanic field contains hundreds of relatively small-volume, widely scattered, mostly basaltic lava flows and cinder cones that range in age from Miocene to Holocene. In southwestern Utah, basalts are synchronous with basin-range deformation and are part of mostly small, bimodal (basalt and high-silica rhyolite) eruptive centers (Christiansen and Lipman, 1972; Rowley and Dixon, 2001). The oldest basalts in southwestern Utah are about 17 Ma (basalt of Harrison Peak; Biek and others, 2009). The youngest dated lava flow in southwest Utah is the 32,000-year-old Santa Clara basaltic lava flow (Willis and others, 2006; Biek and others, 2009), but the Dry Valley and Panguitch Lake lava flows south of Panguitch Lake may be younger still. Red-hot lava flows, an integral part of the Southern Paiute legend “How the whistler [bird] and badger got their homes,” were suggested to relate to the Panguitch Lake-area lava flows (Palmer, 1957; Southern Paiutes lived in southwest Utah beginning about A.D. 1100 [Canaday, 2001]), but it is unlikely the flows are this young. Schulman (1956) briefly reported on 850- to 950-year-old juniper (*Juniperus scopulorum*) trees growing on young lava flows, thus showing that the lava flows are at least that old but still could be many thousands of years old; these lava flows are apparently near Panguitch Lake although definitive sample locations are unavailable (his samples BRY 2104 and BRY 2110, table “Overage drought conifers,” p. 32).

The oldest dated basaltic lava flows in the map area are the Houston Mountain flow (Tbhm), for which we report a new $^{40}Ar/^{39}Ar$ plateau age of 5.27 ± 0.14 Ma, and the 5.3 Ma Dickinson Hill and Rock Canyon flows (Table 1); the undated Sidney Peaks lava flow (Tbsp) may be older still. Stowell (2006) reported an $^{40}Ar/^{39}Ar$ plateau age of 2.78 ± 0.16 Ma for what is likely the Blue Spring Mountain lava flow, and an $^{40}Ar/^{39}Ar$ maximum isochron age of 0.60 ± 0.25 Ma for what is likely the Long Flat lava flow.

Lava flows in the map area typically have a rubbly base, a dense, jointed middle part, and—if not eroded away—a vesicular upper part that has a rough aa (a Hawaiian term for a blocky, jagged flow) or, rarely, a poorly developed pahoehoe (a Hawaiian term for a smooth or ropy flow) surface. Several lava flows, including the Duck Creek and Bowers Knoll lava flows, contain open lava tubes; the best known is Mammoth Cave (6 miles [10 km] northeast of Duck Creek Village). The flows commonly overlie stream-gravel and other surficial deposits. Older lava flows are partly covered by eolian sand and calcic soil (caliche) not shown on this map. Most lava flows are dark gray and fine grained, and contain small olivine phenocrysts and common crystal clusters of olivine, plagioclase, and clinopyroxene. With few exceptions, these lava flows are difficult to distinguish by hand sample alone. They are distinguished for this geologic map by detailed geologic mapping, major- and trace-element geochemistry, and isotopic ages.

The lava flows in the map area provide a "snapshot" of the local landscape as it existed when the flow erupted. Each flow was emplaced in a "geological instant" (most small basaltic volcano vents produce only one eruptive cycle that may last less than a year or as much as a few tens of years in duration), flowed several miles across the landscape, and is resistant to erosion. Because lava flows blocked drainages, streams were shunted to the side where they preferentially eroded adjacent, less resistant sedimentary strata, ultimately leaving the resistant lava flows stranded as elevated, sinuous ridges (called inverted valleys) that mark the location of former channels. Southwest Utah is famous for its classic examples of inverted topography, such as Washington and Middleton Black Ridges near St. George, as first described in detail by Hamblin (1963, 1970, 1987) and Hamblin and others (1981). Classic, if lesser known, inverted valleys are present on the east-tilted Markagunt Plateau as well, as at the distal ends of the Asay Knoll (Qbak), Bowers Knoll (Qbbk), and Coopers Knoll (Qbck) lava flows.

Several lava flows cross and are cut by range-bounding normal faults, including the Water Canyon (Qbw), Summit (Qbs), Red Hills (Qbrh) , Rock Canyon (Tbrc), and Red Canyon (Qbrc) flows. For example, the 0.44 Ma Water Canyon flow crosses a relay ramp between two en echelon sections of the Parowan-Paragonah fault zone; at the mouth of Water Canyon, the flow reveals about 250 feet (75 m) of displacement, yielding a long-term slip rate of about 0.17 mm/yr (about 0.007 in/yr or 550 feet/mya) for the eastern fault strand.

Basaltic magmas are partial melts derived from the compositionally heterogeneous lithospheric mantle, and this, coupled with fractional crystallization, may account for most of the geochemical variability between individual lava flows (Lowder, 1973; Best and Brimhall, 1974; Leeman, 1974; Nealey and others, 1995, 1997; Nelson and Tingey, 1997; Nusbaum and others, 1997; Smith and others, 1999; Downing, 2000; Johnson and others, 2010). Major- and trace-element data for volcanic rocks in the map area will soon be available at http://geology.utah.gov/online/analytical_data.htm. Nb/La ratios for virtually all samples of basaltic and andesitic lava flows from the map area are less than 1.0, thus suggesting a lithospheric mantle source (Fritton and others, 1991). Rock names are from LeBas and others (1986).

QTb **Basaltic lava flow, undivided** (Pleistocene? to Miocene?) – Medium- to dark-gray basalt lava flow that caps a ridge north of Wilson Creek, a southern tributary of Mammoth Creek, about 3 miles (5 km) northwest of Asay Bench; correlation is uncertain, but major- and trace-element geochemistry shows affinities to the 5.3

Ma Houston Mountain lava flow, although its degree of topographic inversion suggests that it is not that old; about 20 to 30 feet (6–9 m) thick.

$Qbpl_1$, $Qbpl_2$, $Qbpl_3$

Panguitch Lake lava flows (upper Holocene? to upper Pleistocene?) – Mapped as three separate lava flows, with $Qbpl_1$ being the youngest; all three flows are mostly unvegetated, blocky, and exhibit steep flow fronts 100 to 200 feet (30–60 m) high: $Qbpl_1$ is dark-gray to black latite (potassium-rich trachyandesite) containing small (1 mm), stubby plagioclase phenocrysts in a glassy to aphanatic groundmass; $Qbpl_2$ and $Qbpl_3$ are dark-gray latite containing small stubby plagioclase and abundant acicular hornblende phenocrysts in a fine-grained groundmass; age uncertain, but may be as young as late Holocene; individual lava flows are typically about 200 feet (60 m) thick.

The $Qbpl_1$ lava flow lacks collapsed lava tubes and exhibits blocky flow lines similar to those of the Dry Valley lava flow (Qbdv). The smaller $Qbpl_2$ lava flow has collapsed lava tubes and partly buries the $Qbpl_3$ lava flow. The $Qbpl_3$ flow, which has abundant collapsed lava tubes and branching distributary lobes, erupted from a vent apparently now concealed by the younger vents of the $Qbpl_1$ and $Qbpl_2$ lava flows (immediately northeast of Miller Knoll, the large cinder cone [Qbmkc] about 3 miles [5 km] south of Panguitch Lake) and flowed northward about 3 miles (5 km) nearly to Panguitch Lake; this is the "northern Panguitch flow" of Stowell (2006).

Qbdv **Dry Valley lava flow** (upper Holocene? to upper Pleistocene?) – Dark-gray latite (potassium-rich trachyandesite) that contains olivine and abundant hornblende phenocrysts in an aphanatic to fine-grained groundmass; forms a thick, blocky, laterally restricted flow west of Black Rock Valley and north of Mammoth Creek that exhibits high, steep flow fronts (except at Dry Valley, immediately west of the vent, where a slightly older more fluid phase is present); upper surface shows prominent arcuate ridges that reveal flow directions, but vent area lacks scoria or cinders and there is no "tuff ring" as stated by Stowell (2006); northern flank of flow is partly vegetated, but upper surface and south-facing slopes are not vegetated; age uncertain, but overlies and is younger than the Miller Knoll lava flow ($Qbmk_2$ – the "arcuate andesite flow" of Stowell, 2006); typically 100 to 120 feet (30–35 m) thick.

$Qbmk_1$, $Qbmk_2$, $Qbmk_3$, Qbmkc

Miller Knoll lava flows and cinder cone (middle Holocene? to upper Pleistocene) – Mapped as three separate lava flows in the Black Rock Valley area south of Panguitch Lake, with $Qbmk_1$ being the youngest flow: $Qbmk_1$ is dark-gray to black andesite that contains small (1 mm), stubby plagioclase phenocrysts in a glassy to aphanatic groundmass; $Qbmk_2$ and $Qbmk_3$ are dark- to medium-gray basaltic trachyandesite containing clusters of olivine, plagioclase, and clinopyroxene phenocrysts in an aphanatic to fine-grained groundmass and includes both sodium-rich (mugearite) and potassium-rich (shoshonite) rock types, locally containing small, thin plagioclase phenocrysts; the $Qbmk_2$ lava flow, the “southern Panguitch flow” of Stowell (2006), yielded preliminary cosmogenic exposure ages of about 37,000 years (Dave Marchetti, Western State College of Colorado, written communication, August 4, 2009); the $Qbmk_2$ and $Qbmk_3$ flows are thus likely late Pleistocene in age; the $Qbmk_1$ flow unit may be as young as middle Holocene; lava flows are typically 30 to 100 feet (10–30 m) thick, but may be thicker where they fill paleotopography.

The $Qbmk_1$ lava flow erupted from a vent near the top of the Miller Knoll cinder cone (Qbmkc, at the northwest end of Black Rock Valley) and forms a blocky, mostly unvegetated flow that looks morphologically similar to, and may be chemically transitional with, latite of the Panguitch Lake lava flows (Qbpl). The much larger $Qbmk_2$ lava flow erupted from vents on the south side of the Miller Knoll cinder cone and flowed about 4 miles (6 km) southeast through Black Rock Valley to Mammoth Creek, forming a young-looking, blocky, poorly vegetated flow that has abundant collapsed lava tubes and branching distributary lobes. The $Qbmk_3$ lava flow erupted from a vent now concealed by the Miller Knoll cinder cone; the lava flow is mostly well vegetated and was the first flow to block Blue Spring Valley—the western part of this flow is partly covered by old mixed lacustrine and alluvial deposits (Qlao) that we interpret as having accumulated upstream of the lava-flow dam.

The southern extent of the $Qbmk_2$ lava flow along Mammoth Creek was clearly limited by pre-existing topography of the pink member of the Claron Formation, but the flow now lies at the modern base level of Mammoth Creek, suggesting that the lava flow once blocked Mammoth Creek, which has since eroded the adjacent, less-resistant Claron strata (lacustrine sediments are absent upstream of the lava flow along Mammoth Creek, but stream terraces there may record partial infilling and subsequent exhumation of the valley).

Qbnl, Qbnlc

Navajo Lake lava flows and cinder cone (upper Pleistocene?) – Medium- to dark-gray mugearite (sodium-rich basaltic trachyandesite) containing clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; some lava flows contain common small plagioclase phenocrysts; lava flows (Qbnl) erupted from vents at a cinder cone (Qbnlc) about 3 miles (5 km) north of Navajo Lake (Moore and others, 2004) and coalesced into flow complexes not mapped separately; margins of flows typically form steep, blocky flow fronts 10 to 30 feet (3–9 m) high; cinder cone is well vegetated; lava flows are locally well vegetated, but more commonly barren and characterized by a rough, blocky surface; vegetated areas collect wind-blown sediment that forms a sparse soil cover on parts of the flow; age uncertain, but likely late Pleistocene based on degree of incision and weathering, although Moore and others (2004) considered the lava flow as probably Holocene; lava flows are typically several tens of feet thick, but thicker where they fill paleotopography.

Qbrd, Qbrdc

Red Desert lava flows and cinder cone (upper Pleistocene?) – Medium- to dark-gray basalt and basaltic andesite that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; some lava flows contain common small plagioclase phenocrysts; lava flows (Qbrd) erupted from vents at a cinder cone (Qbrdc) nearly 6 miles (10 km) north of Navajo Lake (Moore and others, 2004), and from a small vent about 3 miles (5 km) to the southeast, and coalesced into flow complexes not mapped separately; margins of flows typically form steep, blocky flow fronts 10 to 30 feet (3–9 m) high; cinder cone is well vegetated; lava flows are locally well vegetated, but more commonly are barren and have a rough, blocky surface; vegetated areas collect wind-blown sediment that forms a sparse soil on parts of the flow; age uncertain, but lava flows are likely late Pleistocene based on degree of incision and weathering, although Moore and others (2004) considered the lava flow as probably Holocene; lava flows are typically several tens of feet thick, but thicker where they fill paleotopography.

Qbhk, Qbhkc

Henrie Knolls lava flows and cinder cones (upper Pleistocene) – Medium- to dark-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; some lava flows, particularly those between Duck Creek Sinks and Dry Camp Valley Spring (about 4 to 5 miles [6–8 km] east and northeast of Navajo Lake), also contain common plagioclase phenocrysts and have a slightly coarser groundmass; lava flows that erupted from the northeasternmost group of cinder cones, including Henrie Knolls, tend to be of basaltic andesite composition; margins of flows typically form steep, blocky flow fronts 10 to 30 feet (3–9 m) high; cinder cones are well vegetated; lava flows are locally well vegetated but more commonly barren, exhibiting a rough, blocky surface; age unknown, but probably late Pleistocene because the north end of flow complex is incised by Tommy Creek and capped by level 4 stream-terrace deposits (Biek and others, 2011, here mapped as Qat) assumed to be of late Pleistocene age; sample HK092106-1 near Henrie Knolls yielded a low-precision $^{40}Ar/^{39}Ar$ age of 0.058 ± 0.035 Ma (UGS and NMGRL, 2009); lava flows are typically several tens of feet thick, but likely exceed 200 feet (60 m) thick where they fill paleotopography.

The wide chemical variation of the Henrie Knolls lava flows (Qbhk) reflects the fact that these flows erupted from at least 20 separate vents marked by cinder cones (Qbhkc), including the largest two cones at Henrie Knolls, in the northeast part of the flow complex. The cinder cones are strikingly aligned along a northeast trend, subparallel to mapped normal faults in the quadrangle. Although no fault that postdates eruption of the Henrie Knolls lava flows has been identified along this trend, a concealed, unmapped fault likely controls the alignment of vents. The southernmost of the Henrie Knolls lava flows blocked the Navajo Lake and nearby Dry Valley drainages, forming Navajo Lake and intermittent Cow Lake.

Qbmc, Qbmcc

Midway Creek lava flow and cinder cones (Pleistocene) – Medium- to dark-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; lava flow (Qbmc) erupted from a vent at a cinder cone (Qbmcc) and is partly covered by the Navajo Lake lava flow (Qbnl) (Moore and others, 2004); this cinder cone may also be the source of the Duck Creek lava flow (Qbdc); lava flow is typically several tens of feet thick, but thicker where it fills paleotopography.

Qbde, Qbdec

Deer Valley lava flow and cinder cone (Pleistocene) – Medium- to dark-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; small lava flow (Qbde) erupted from a vent at a cinder cone (Qbdec) 1.5 miles (2.5 km) north of Navajo Lake; lava flow is typically several tens of feet thick, but thicker where it fills paleotopography.

Qbho, Qbhoc

Horse Pasture lava flow and cinder cone (Pleistocene) – Medium- to dark-gray basalt and hawaiite (sodium-rich trachybasalt) containing clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; lava flow (Qbho) erupted from a vent at a cinder cone (Qbhoc) 4 miles (6 km) north of Navajo Lake; this cinder cone may also be the source of the Duck Creek lava flow (Qbdc); lava flow is typically several tens of feet thick, but thicker where it fills paleotopography.

Qbdc **Duck Creek lava flow** (Pleistocene) – Medium-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts and abundant small plagioclase phenocrysts in a fine-grained groundmass; lava flow is typically partly concealed by a veneer of unmapped surficial deposits of alluvial, colluvial, and eolian origin; maximum exposed thickness is about 15 feet (5 m) near Aspen Mirror Lake, but likely several tens of feet thick where it fills paleotopography in the Duck Creek drainage.

The vent location of the Duck Creek lava flow is unknown, but it may be concealed by the Henrie Knolls (Qbhk) or Navajo Lake (Qbnl) lava flows. Alternatively, geochemical data suggest that the Duck Creek lava flow may be the distal part of either the Midway Creek or Horse Pasture lava flows. Regardless, the lava flowed east down the ancestral Duck Creek drainage and continued northeastward to at least the Bowers Flat area at the west edge of the Asay Bench quadrangle. The lava flow contains a long, open lava tube near Aspen Mirror Lake, just west of Duck Creek village (U.S. Forest Service restricts access). The age of the Duck Creek flow is uncertain, but it locally covers the Bowers Knoll lava flow (Qbbk) and in turn is locally covered by the Henrie Knolls lava flow (Qbhk), thus is probably upper to middle Pleistocene. However, Johnson and others (2010) suggested that the distal end of the Bowers Knoll flow as mapped here, including the part that contains Mammoth Cave, may be the Duck Creek flow—if so, incision there suggests that the Duck Creek flow is about 500,000 years old, far older than the degree of incision suggests along the upstream part of the flow.

Qbsk, Qbskc

Strawberry Knolls lava flows and cinder cones (Pleistocene) – Medium- to dark-gray potassic trachybasalt that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; lava flows (Qbsk) erupted from Strawberry Knolls (Qbskc), two cinder cones located about 2 miles (3 km) east of Duck Creek village, and flowed mostly northeast along Strawberry Creek to Uinta Flat; age uncertain, but cinder cones are well vegetated and flow is incised by Strawberry Creek as much as 40 feet (12 m) at its downstream end and so is probably upper to middle Pleistocene; lava flows are typically 20 to 30 feet (6–9 m) thick, but doubtless many tens of feet thick near vent areas.

Qblhc **Lake Hollow cinder cone** (Pleistocene) – Forms a small, partly eroded cinder cone about 1.5 miles (3 km) north of Mammoth Creek and east of Black Rock Valley, with a small lava flow (not differentiated on this map) at the base of the cone of medium- to dark-gray hawaiite (sodium-rich trachybasalt) that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; vent is on-trend with the Henrie Knolls lava flows, to which it may be related; age unknown, but likely late to middle Pleistocene based on its degree of erosion; lava flow is less than about 20 feet (6 m) thick.

Qbef, Qbefc

East Fork Deep Creek lava flow and cinder cone (Pleistocene) – Medium- to dark-gray, fine-grained olivine basalt lava flow (Qbef) west of Navajo Lake; cinder cone (Qbefc) is deeply eroded due to its location just below the western escarpment of the Markagunt Plateau, just west of Navajo Lake; the distal southern end of this flow was called the Three Creeks lava flow by Biek and Hylland (2007), which they estimated to be less than 300,000 years old based on degree of incision and comparison with nearby dated lava flows; lava flow is probably 20 to 40 feet (6–12 m) thick.

Qbw, Qbwc

Water Canyon lava flow and cinder cone (middle Pleistocene) – Dark-gray potassic trachybasalt and shoshonite (potassium-rich basaltic trachyandesite) that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; quartz xenocrysts common; lava flow (Qbw) erupted from cinder cone (Qbwc) in Water Canyon about 3 miles (5 km) southeast of Paragonah (Maldonado and Moore, 1995); Fleck and others (1975) reported a K-Ar age (corrected according to Dalrymple, 1979) of 0.45 ± 0.04 Ma for this flow; lava flow is as much as 200 feet (60 m) thick where it partly fills Water Canyon.

Qbbk, Qbbkc

Bowers Knoll lava flow and cinder cones (middle Pleistocene) – Medium-gray mugearite (sodium-rich basaltic trachyandesite) containing abundant clusters of olivine, plagioclase, and clinopyroxene phenocrysts in a fine-grained groundmass; lava flow erupted from Bowers Knoll, a cinder cone (Qbbkc) about 3 miles (5 km) northeast of Duck Creek village; forms rugged, heavily vegetated, blocky surface having steep flow fronts 40 feet (12 m) or more high; as mapped, contains Mammoth and Bower caves, large open lava tubes, but that part of the flow may belong to the Duck Creek flow (Johnson and others, 2010); age uncertain, but locally underlies the Duck Creek lava flow (Qbdc), so is probably middle Pleistocene; Best and others (1980) reported a K-Ar age of 0.52 ± 0.05 Ma for the nearby Asay Knoll lava flow (Qbak), which exhibits a similar degree of incision and weathering; typically 40 feet (12 m) or more thick near flow margins, but may exceed 100 feet (30 m) thick near the central part of the flow.

Qbrc **Red Canyon lava flow and cinders** (middle Pleistocene) – Medium- to dark-gray andesite and mugearite (sodium-rich basaltic trachyandesite); lava flow apparently erupted from several vent areas (which denote abundant cinders but no cone morphology) on the hanging wall of the Sevier fault and flowed eastward across the fault where it caps Black Mountain near the entrance to Red Canyon; Lund and others (2008) reported $^{40}Ar/^{39}Ar$ ages of 0.49 ± 0.04 Ma (footwall) and 0.51 ± 0.01 Ma (hanging wall), and Best and others (1980) reported a K-Ar age of 0.56 ± 0.07 Ma for this flow on the hanging wall; Lund and others (2008) documented 630 to 740 feet (192–225 m) of displacement on the flow, yielding vertical-slip-rate estimate of 0.38–0.44 mm/yr; lava flow is typically about 80 feet (25 m) thick, but thicker near vent areas.

Qbak, Qbakc

Asay Knoll lava flow and cinder cone (middle Pleistocene) – Medium- to dark-gray potassic trachybasalt and shoshonite (potassium-rich basaltic trachyandesite) that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; lava flow (Qbak) erupted from Asay Knoll cinder cone (Qbakc) and covers Asay Bench; Best and others (1980) reported a K-Ar age of 0.52 ± 0.05 Ma for this flow; lava flow is typically 20 to 30 feet (6–9 m) thick, but is doubtless many tens of feet thick near vent area.

Qbck, Qbckc

Cooper Knoll lava flow and cinder cone (middle Pleistocene) – Medium-gray basalt that contains clusters of olivine, plagioclase, and clinopyroxene phenocrysts in a fine-grained groundmass; lava flow (Qbck) erupted from a vent at a cinder cone (Qbckc) on the south flank of Cooper Knoll, about 1 mile (1.6 km) southeast of Panguitch Lake; overlies stream gravels containing rounded pebbles and cobbles of the Isom Formation, mafic and intermediate volcanic rocks of the Mount Dutton Formation, chalcedony, and minor quartzite; age uncertain, but may be about 500,000 years old based on comparison with the similarly incised Asay Bench lava flow (Qbak) for which Best and others (1980) reported a K-Ar age of 0.52 ± 0.05 Ma; lava flow is about 20 to 40 feet (6–12 m) thick.

Qbwf, Qbwfc

Webster Flat lava flow and cinder cone (middle Pleistocene) – Medium-gray, fine-grained olivine basalt with small plagioclase phenocrysts; lava flow (Qbwf) erupted from vent at cinder cone (Qbwfc) about 1 mile (1.6 km) east of Black Mountain in the southwest corner of the map area and flowed mostly south down the Kolob Terrace; age uncertain, but probably about 500,000 years old based on comparison with nearby dated flows and its degree of dissection; lava flow is typically several tens of feet thick.

Qbal, Qbalc

Aspen Lake lava flow and cinder cone (middle Pleistocene) – Medium-gray, fine-grained olivine basalt with small plagioclase phenocrysts; lava flow (Qbal) erupted from vent at cinder cone (Qbalc) about 1 mile (1.6 km) south of Black Mountain in the southwest corner of the map area and flowed mostly south down the Kolob Terrace; age uncertain, but probably about 500,000 years old based on comparison with nearby dated flows and its degree of dissection; lava flow is typically several tens of feet thick.

Qblf, Qblfc

Long Flat lava flow and cinder cones (middle Pleistocene) – Medium-gray basalt to hawaiite (sodium-rich trachybasalt) that contains clusters of olivine and clinopyroxene phenocrysts; lava flow (Qblf) erupted mostly from hills 10,392 and 10,352 (Brian Head 7.5' topographic quadrangle map), which are two cinder cones (Qblfc) near Long Flat about 3 miles (5 km) east of Brian Head peak; a third, smaller cinder cone is near the southeast margin of the flow near State Highway 143; Stowell (2006) reported an $^{40}Ar/^{39}Ar$ maximum isochron age of 0.60 ± 0.25 Ma for sample LEA71SS2, which is likely from the Long Flat lava flow, but minor- and trace-element signatures of the Long Flat and nearby Hancock Peak flows are similar and Stowell's sample location lacks precision to be properly located, thus the age of the Long Flat flow is uncertain; parts of the lava flow are covered by Pinedale-age glacial till and glacial outwash, and the cinder cones appear to be more heavily eroded than the nearby Hancock Peak cinder cone (Qbhpc); the northeast flank of hill 10,392 is conspicuously truncated and it may have been eroded by an earlier glacial advance (if so, likely the Bull Lake [Illinoian or MIS 6] advance); lava flow is several tens of feet thick.

Qbwk, Qbwkc

Wood Knoll lava flow and cinder cone (middle Pleistocene) – Medium- to dark-gray, fine-grained olivine basalt; lava flow (Qbwk) erupted from a vent at Wood Knoll, a cinder cone (Qbwkc) about 2 miles (3 km) southwest of Cedar Breaks National Monument, and flowed northwest into Long Hollow; a remnant of the flow, perched 1100 feet (335 m) above the junction of Ashdown Creek and Coal Creek, yielded an $^{40}Ar/^{39}Ar$ age of 0.63 ± 0.10 Ma and a long-term down cutting rate of 0.53 mm/yr (about 21 inches per thousand years or 1700 ft/myr), inferred to be a minimum rate of relative uplift on the Hurricane fault to the west (Lund and others, 2007); lava flow is typically several tens of feet thick, but is as much as about 300 feet (90 m) thick where it fills the ancestral Coal Creek channel.

Qbub, Qbubc

Upper Bear Springs lava flows and cinder cones (middle to lower Pleistocene) – Medium- to dark-gray, fine-grained olivine basalt; lava flows (Qbub) erupted from vents at cinder cones (Qbubc) about 2 miles (3 km) southwest of Navajo Lake and flowed mostly south onto the Kolob Terrace; probably about 750,000 years old because they appear to be the same lava flows as those at Horse Knoll (Sable and Hereford, 2004; Doelling, 2008), which yielded a K-Ar age of 0.81 ± 0.05 Ma and an $^{40}Ar/^{39}Ar$ age of 0.73 ± 0.02 Ma (Biek and Hylland, 2007; UGS and NMGRL, 2008); lava flows are several tens of feet thick.

Qbbm **Black Mountain lava flow** (middle to lower Pleistocene) – Medium-gray, fine-grained olivine basalt with small plagioclase and pyroxene phenocrysts; lava flow caps the northwest sloping surface of Black Mountain in the southwest corner of the map area; vent unknown but may be concealed by nearby younger lava flows or surficial deposits to the southeast; yielded K-Ar ages of 0.80 ± 0.24 (Anderson and Mehnert, 1979) and 0.87 ± 0.24 Ma (Best and others, 1980); typically several tens of feet thick.

$Qbhp_1$, $Qbhp_2$, Qbhpc

Hancock Peak lava flows and cinder cone (middle to lower Pleistocene) – Medium-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; based on chemistry and morphology the map unit is divided into two flows, both of which are well vegetated; erupted from Hancock Peak, a large, well-preserved cinder cone (Qbhpc) 5 miles (8 km) southeast of Brian Head peak; $Qbhp_1$ appears to overlie $Qbhp_2$ and extends farther downstream where it caps an inverted valley about 600 feet (180 m) above Mammoth Creek just north of the community of Mammoth Creek; age unknown, but estimated to be middle to early Pleistocene based on comparison with the 60,000-year-old Long Flat lava flow (Qblf) and the 2.8 Ma Blue Spring Mountain lava flow (Tbbm); lava flows are typically several tens of feet thick, but likely exceed 100 feet (30 m) thick where they fill paleotopography.

Qbtp **The Pass lava flow** (Pleistocene?) – Medium- to dark-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; caps a small knob just south of The Pass, about 1 mile (1.6 km) east of Panguitch Lake that Wagner (1984) interpreted as a small gabbroic intrusion, but that appears to be a flow remnant partly involved in a landslide; chemically similar to the 5.3 Ma Houston Mountain lava flow (Tbhm), but source is uncertain; probably about 50 feet (15 m) thick.

Qbc **First Left Hand Canyon vent** (middle to lower Pleistocene?) – Forms deeply eroded basaltic vent area. Lower part contains abundant angular blocks of Claron Formation and basaltic volcanic rocks and minor rounded quartzite pebbles and cobbles; the whole mass is cut by several basaltic dikes; some blocks are as large as 12 feet (4 m) in size, but most are pebble to small cobble size; unbedded and appears to be a volcanic mudflow deposit. Upper part is mostly basaltic blocks and fewer Claron blocks, welded into scoriaceous matrix. Unconformably overlies the lower conglomerate and middle sandstone members of the Grand Castle Formation on the northwest side of Henderson Hill in First Left Hand Canyon, about 4 miles (6 km) south of Parowan; lies about 600 feet (180 m) above the modern drainage, and may be associated with adjacent basaltic dikes; about 400 feet (120 m) thick.

Qbs, Qbsc

Summit lava flow and cinder cone (lower Pleistocene) – Medium- to dark-gray, fine-grained olivine basalt that Maldonado and others (1997) referred to as the Cinder Hill cone and flow; lava flow (Qbs) erupted from a vent at a cinder cone (Qbsc) at the base of the Hurricane Cliffs, about 2 miles (3 km) southwest of Summit; lava flow also crops out at the southeast margin of the Red Hills and is presumed to underlie the southern part of the Parowan Valley graben, where it is displaced by graben-bounding faults; yielded K-Ar ages of 1.00 ± 0.16 Ma and 0.94 ± 0.14 Ma (Anderson and Mehnert, 1979); lava flow is typically several tens of feet thick.

Qbe **Elliker Basin lava flow** (lower Pleistocene) – Medium- to dark-gray, fine-grained olivine basaltic trachyandesite; vent area unknown, but minor scoria and blocky flow breccia is present on the north rim of Elliker Basin, suggesting that the vent could underlie the basin, which is southwest of Summit; yielded K-Ar ages of 1.00 ± 0.16 Ma and 1.11 ± 0.11 Ma (Anderson and Mehnert, 1979); typically several tens of feet thick.

Qbrh, Qbrhc

Red Hills lava flows and cinder cones (lower Pleistocene) – Medium- to dark-gray, fine-grained basaltic andesite with small olivine and plagioclase phenocrysts; lava flows (Qbrh) erupted from vents at three cinder cones (Qbrhc) in the southern Red Hills (Rowley and Threet, 1976); lava flows are mostly covered by eolian sand and silt, and locally by small areas of fan alluvium, but due to map scale only the larger of such areas are mapped; lava flow is cut by faults associated with the Red Hills horst and graben; yielded K-Ar ages of 1.28 ± 0.4 Ma (Anderson and Mehnert, 1979) and 1.30 ± 0.4 Ma (Best and others, 1980); lava flow is typically several tens of feet thick.

Tbbm, Tbbmc

Blue Spring Mountain lava flow and cinder cone (Pliocene) – Medium-gray hawaiite and mugearite (sodium-rich trachybasalt and basaltic trachyandesite, respectively) lava flow (Tbbm) that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; erupted from vents at a cinder cone (Tbbmc) on Blue Spring Mountain and flowed east and south, mostly toward the ancestral Mammoth Creek drainage; an erosional outlier caps Mahogany Hill, about 500 feet (150 m) above Mammoth Creek east of its intersection with Black Rock Valley; the cinder cone is heavily eroded and the lava flow is well vegetated; between Blue Spring Mountain and Blue Spring Valley, the flow is involved in a large landslide complex, which slid on the underlying Brian Head Formation; lava flow is typically several tens of feet thick, but is doubtless thicker near the vent area and where it fills paleotopographic lows.

Stowell (2006) reported an $^{40}Ar/^{39}Ar$ plateau age of 2.78 ± 0.16 Ma for what is likely the Blue Spring Mountain lava flow, but Stowell's sample location lacks precision to be properly located, thus age is uncertain. Based on their similar chemistry, the map unit includes a northeast-trending dike at the north end of Blue Spring Valley and a small flow remnant a few tens of feet above Blue Spring Creek (Biek and Sable, in preparation). If the Blue Spring Creek remnant is indeed part of the 2.8-million-year-old Blue Spring Mountain lava flow, it means that the Blue Spring Valley area has been a topographic low for nearly the past 3 million years, an unlikely scenario.

Tbfr **Fivemile Ridge lava flow** (Pliocene?) – Medium-gray basalt containing clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; erupted from deeply eroded vent area on Fivemile Ridge about 8 miles (13 km) northeast of Panguitch Lake; appears to be gently folded into a northeast-trending syncline; age uncertain, but degree of incision suggests that it is Pliocene in age; typically several tens of feet thick.

Tbhb **Horse Bench lava flow** (Pliocene?) – Medium-gray andesite that caps Horse Bench, about 8 miles (13 km) north-northeast of Panguitch Lake; based on major- and trace-element chemistry of a single sample, appears to be a different flow than the Fivemile Ridge flow, but location of vent is unknown; age uncertain, but degree of incision suggests that it is Pliocene in age; typically several tens of feet thick.

Tbhm **Houston Mountain lava flow** (lower Pliocene to upper Miocene) – Medium-gray basalt containing clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; unconformably overlies the Brian Head Formation (Tbhv) and Leach Canyon Formation (Tql) along the west edge of Blue Spring Mountain; an erosional outlier on the south side of Clear Creek, about 3 miles (5 km) west-northwest of Panguitch Lake, contains abundant 1- to 2-mm-long plagioclase phenocrysts, but is otherwise chemically similar to the Houston Mountain flow; also caps Houston Mountain (about 6 miles [10 km] east of Cedar Breaks National Monument) and other hills of lower elevation to the south (about 3 miles [5 km] northeast of Navajo Lake), where it is typically platy weathering; source vent unknown and margins of lava flow are entirely eroded away, but elevation of remnants suggests flow was derived from the west of its current exposures, probably in the Brian Head quadrangle, likely at a vent now eroded and concealed by younger deposits; sample HK092006-3 yielded an $^{40}Ar/^{39}Ar$ whole-rock age of 5.27 ± 0.14 Ma (UGS and NMGRL, 2009); maximum thickness is about 140 feet (43 m) at Houston Mountain.

Tbdh, Tbdhc

Dickinson Hill lava flows and cinder cones (lower Pliocene to upper Miocene) – Medium-gray basalt containing clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; interbedded with upper Tertiary fan alluvium (Taf); lava flows (Tbdh) erupted from vents in eroded cinder cones (Tbdhc) southwest of Panguitch; Anderson and Christenson (1989) reported a K-Ar age of 5.3 ± 0.5 Ma for one of these lava flows; major- and trace-element chemistry and age are similar to that of the nearby Rock Canyon lava flow, making differentiation of the two lava flows uncertain in the area southeast of Panguitch; exposed thickness of lava flows is as much as 65 feet (20 m), and cinder deposits are 3 to 10 feet (1–3 m) thick.

Tbrc, Tbrcc

Rock Canyon lava flow and cinder cone (lower Pliocene to upper Miocene) – Medium-gray potassic trachybasalt and basalt that contains clusters of olivine and clinopyroxene and small plagioclase phenocrysts in a fine-grained groundmass; lava flow (Tbrc) is interbedded with upper Tertiary fan alluvium (Taf); erupted from a cinder cone (Tbrcc) about 4 miles (6 km) north-northwest of Hatch; apparent age and major- and trace-element chemistry are similar to those of the nearby 5.3 Ma Dickinson Hill lava flow (Tbdh); query indicates our uncertainty in correlating these two flows in their area of possible overlap; maximum exposed thickness is about 100 feet (30 m).

Based on limited geochemistry, the Rock Canyon lava flow may be the same lava flow exposed in the footwall and hanging wall of the Sevier fault just south of State Route 12 and Red Canyon. Lund and others (2008) reported $^{40}Ar/^{39}Ar$ ages on the flow near Red Canyon of 4.94 ± 0.03 Ma (footwall outcrop) and 4.98 ± 0.03 Ma (hanging wall outcrop). If this correlation is correct, it implies that the valley of the Sevier River and the footwall of the Sevier fault zone did not exist as topographic barriers to eastward movement of the Rock Canyon lava flow in early Pliocene time, about 5 million years ago. It further implies that the Rock Canyon lava flow underlies parts of Sevier valley. Regardless, Lund and others (2008) documented 775 to 1130 feet (237–344 m) of displacement on the flow at this location, yielding vertical-slip-rate estimate of 0.05–0.07 mm/yr, significantly lower than the estimate determined from the nearby but younger 0.5 Ma Red Canyon lava flow.

Tbsp **Sidney Peaks lava flow** (lower Pliocene to upper Miocene) – Medium-gray basalt containing clusters of olivine and clinopyroxene phenocrysts as much as ¼ inch (5 mm) in diameter in a fine-grained groundmass; forms deeply dissected flow and flow breccia that unconformably overlie the Markagunt Megabreccia; deposit just northeast of Sidney Peaks, which unconformably overlies the Leach Canyon Formation, consists of lava blocks in a cinder matrix, is locally cut by basaltic dikes, and may be a deeply eroded vent area; as much as 80 feet (25 m) thick.

QTr **Relict Houston Mountain lava flow** (Holocene to Pliocene) − Mapped about 4 miles (7 km) north-northeast of Navajo Lake, where blocky remnants of the 5.3 Ma Houston

Mountain lava flow (Tbhm) have been let down by sapping and dissolution of underlying beds; angular to subangular blocks of the lava flow, typically 3 feet (1 m) or less in diameter but locally as large as about 12 feet (4 m), locally form a basaltic pavement on the white member of the Claron Formation, but typically they are widely scattered; other than uncommon small fragments of chalcedony (itself likely the remains of the Brian Head Formation once buried by the Houston Mountain lava flow), no other exotic rock types are present; map unit probably formed as former basalt-capped hilltops succumbed to chemical weathering of carbonate beds in the underlying Claron Formation and concomitant hillslope erosion, undermining the lava flow and scattering resistant basalt blocks over the underlying bedrock, processes that began following development of inverted topography now capped by the Houston Mountain lava flow; unmapped colluvium derived from this unit blankets much of the nearby Claron Formation; typically less than a few feet thick.

Also mapped on the south side of Blue Spring Mountain (about 5 miles [8 km] southwest of Panguitch Lake), where the deposit is of likely Quaternary age and consists of blocks of the Blue Spring Mountain lava flow (Tbbm) that conceal the upper part of the white member of the Claron Formation and possibly the lower part of the Brian Head Formation.

QTbx **Markagunt Megabreccia residuum** (Holocene to Pliocene?) – Mapped south of the outcrop belt of the Markagunt Megabreccia (Tm), principally at and near the west rim of the Markagunt Plateau, but also mapped where it caps several small hills south of Panguitch Lake and in the upper reaches of Rock Canyon, south of Haycock Mountain. Consists of two units not mapped separately: (1) large blocks and rubble of the Isom Formation present in the northeast part of Cedar Breaks National Monument, and (2) an unconsolidated mix of Isom boulders and minor Brian Head debris present in the southern part of the monument and in the deposits near Panguitch Lake. In both units, Isom blocks are subangular and locally as much as 16 feet (5 m) in size, but in the northeast part of the monument, rafted Isom blocks are as much as several hundred feet in extent; many of the Isom blocks are internally brecciated on a fine scale, then rehealed by silicification to become a resistant rock (Hatfield and others, 2010), presumably by devitrification of the Isom ash flow itself (the brecciation is a direct result of formation of the Markagunt Megabreccia, discussed below). Maximum thickness is about 150 feet (45 m) at Blowhard Mountain immediately south of Cedar Breaks National Monument, but most deposits are 5 to 30 feet (2–9 m) thick.

Exposures on the west side of Blowhard Mountain reveal large fractured blocks of Brian Head tuffaceous mudstone, sandstone, micritic limestone, and chalcedony, with some blocks as large as 100 feet (30 m) long, in addition to the ubiquitous, angular Isom boulders. There, the map unit overlies alluvial boulder gravel (undifferentiated from the residuum) as much as about 50 feet (15 m) thick that consists of subrounded Isom Formation clasts, minor Brian Head limestone and chalcedony clasts, and, near the base of the deposit, rare Claron clasts. Isom clasts are commonly 2 to 3 feet (0.5–1 m) in diameter and locally as much as 9 feet (3 m) long and include at least one large boulder of Isom flow breccias similar to that at Brian Head peak. No other clast types are present. Much of the west side of this outcrop belt at Blowhard Mountain is involved in landslides, many with historical movement, but the gravel is clearly part of a channel eroded into the Claron Formation and overlain by mass-wasting deposits composed of Isom and Brian Head debris.

Between Blowhard Mountain and Long Valley Creek, these residuum deposits form an extensive, hummocky surface draped over the Claron Formation. Elsewhere on Blowhard Mountain and areas to the east and south, the map unit is characterized by abundant or scattered, large, locally internally brecciated, angular Isom boulders that litter the surface. The hummocky surface is due to dissolution and collapse of underlying Claron limestone, which created numerous sinkholes in this area (Moore and others, 2004; Hatfield and others, 2010; Spangler, 2010), but the surface is also likely due in part to ongoing slumping and slope creep that results from admixed tuffaceous Brian Head strata (Moore, 1992).

The large blocks of Isom in this map unit in and near the northeast part of Cedar Breaks National Monument rest unconformably on Brian Head and Claron strata, whereas not far to the north, at a higher elevation, the main mass of the Markagunt Megabreccia rests on Leach Canyon Formation. Because the southern margin of the Megabreccia (and underlying regional ash-flow tuffs) is erosional in nature, we do not know its southern depositional limit. However, because debris from the Leach Canyon Formation is missing in areas mapped as QTbx in the northeast part of Cedar Breaks National Monument and at and near Blowhard Mountain, it seems likely that the Leach Canyon (and underlying in-place Isom) pinched out southward against paleotopography and did not extend much farther south than its present-day outcrop. Because there is no evidence for a post-Leach Canyon (but pre-Markagunt Megabreccia) unconformity that cuts out strata southward across the west edge of the Markagunt Plateau, lead-author Biek interprets the large Isom blocks to be old landslide remnants that are at a lower topographic and structural level than the main mass of the Markagunt Megabreccia. In this interpretation, the large Isom blocks and Isom and Brian Head debris are inferred to be derived from northward retreat of the erosional escarpment that stretches from Brian Head peak eastward to Haycock Mountain. Thus in this view, similar to that suggested by Moore (1992) and Sable and Maldonado (1997a), the map unit is a remobilized part of the Markagunt Megabreccia, the southern extent of which was emplaced on a paleohigh of Brian Head strata that served to constrain the southern limit of the Isom and Leach regional ash-flow tuffs. The Megabreccia has since been let down to its present position principally by landsliding in late Tertiary and Quaternary time, with smectitic clays of the Brian Head Formation initially providing the weak shear surface for downslope movement of the blocks, which were then further dispersed by colluvial and slope-creep processes. An alternative interpretation, however, suggests that the blocks are a bona fide part of the Miocene Markagunt Megabreccia (Moore and others, 2004; Hatfield and others, 2010; Rowley and others, in preparation), which thus must have been emplaced as far south as Blowhard Mountain; subsequent weathering and sapping of the Megabreccia and underlying Claron Formation then spread debris southward to the area beyond State Route 14. Yet another interpretation is that the map unit may be the distal remains of debris avalanche deposits at the south margin of the Markagunt Megabreccia. Our differences in interpretation reflect our incomplete understanding of these deposits.

QTap **High-level pediment alluvium** (Pleistocene and Pliocene?) – Moderately sorted, subrounded to rounded pebble to boulder gravel and sand that form a gently east-dipping, locally resistant cap on upper Tertiary fan alluvium (Taf) near the east margin of the Markagunt Plateau; surface of deposit typically covered by veneer of pebble and cobble residuum; divisible into two different levels (Moore and Straub, 1995), but undivided here due to map scale; deposited principally as debris flows, debris floods, and in ephemeral stream channels; probably less than 20 feet (<6 m) thick.

QTh **Basin-fill deposits of Long Hill** (Pleistocene and Pliocene?) – Poorly sorted, poorly stratified, boulder- to clay-size sediment containing subangular to subrounded clasts preserved in down-dropped blocks on the west side of the Red Hills; northern exposures consist predominantly of volcanic clasts, some as much as 3 feet (1 m) in diameter, whereas southern exposures contain abundant quartzite cobbles in a reddish-brown calcareous matrix; original depositional form is not preserved; interpreted to represent deeply eroded basin-fill deposits deposited principally as debris flows and debris floods on large alluvial fans; Maldonado and Williams (1993a) mapped kilometer-scale blocks of Oligocene and Miocene ash-flow tuffs within this basin-fill unit that they interpreted to be gravity-slide blocks of Pliocene or Pleistocene age; lead author Biek reinterprets these blocks simply as autochthonous normal-fault-bounded blocks partly covered by basin-fill deposits; exposed thickness as much as about 300 feet (90 m).

TERTIARY

Taf **Upper Tertiary fan alluvium** (Pliocene to Miocene) – Moderately to poorly consolidated, brown and grayish-brown sandstone, siltstone, pebbly sandstone, and conglomerate that form an incised, east-tilted alluvial-fan surface of low, rounded hills along the west side of Sevier valley; clasts are of various volcanic rocks (95%) and about 5% quartzite and sandstone (Kurlich and Anderson, 1997); clasts were derived from the west and north from erosion of the Mount Dutton Formation and regional ash-flow tuffs and deposited as aggrading alluvial fans, possibly in a structurally closed basin later incised by through-going drainage of the Sevier River (Moore and Straub, 1995; Kurlich and Anderson, 1997); includes uncommon, thin, ash-fall tuff beds; interbedded with upper Tertiary basaltic lava flows (including the Rock Canyon lava flows [Tbrc] and the 5.3 Ma Dickinson Hill lava flows [Tbdh]) and uncommon, thin, lenticular beds of lacustrine limestone; east part of the outcrop belt locally includes upper Tertiary stream alluvium representing an axial valley stream; unconformably overlies Claron, Brian Head, Isom, and Limekiln Knoll strata and locally capped by pediment deposits (QTap); as much as 760 feet (230 m) thick in the Hatch quadrangle (Kurlich and Anderson, 1997) and at least 1000 feet (300 m) thick in the Panguitch 7.5' quadrangle (Moore and Straub, 1995).

Previously referred to as the Sevier River Formation, which was named by Callaghan (1938) for partly consolidated basin-fill deposits near Sevier, Utah, on the north side of the Marysvale volcanic complex (see, for example, Anderson and Rowley, 1975; Anderson and others, 1990a; Moore and others, 1994; Rowley and others, 1994a), a name that formerly had value in reconnaissance-scale studies in the High Plateaus; in and near its type area, the formation contains airfall tuffs that have fission-track and K-Ar ages of 14 and 7 Ma and basaltic lava flows that have K-Ar ages of 9 and 7 Ma (Steven and others, 1979; Best and others, 1980; Rowley and others, 2002). In later, more detailed mapping in the High Plateaus, the name Sevier River Formation was restricted to its type area for older basin-fill sediments deposited in post-20 Ma basins that preceded development of the present topography (Rowley and others, 2002); later basin-fill deposits of the main phase of basin-range deformation in the northern Marysvale area were referred to as "sedimentary basin-fill deposits (QTs)" (Rowley and others, 2002). J.J. Anderson (verbal communication, November 16, 2004) referred to these deposits in the Panguitch area as the Panguitch gravels. Rowley and others (1981) used K-Ar ages of mapped volcanic rocks in the Sevier Plateau to the north to constrain the main phase of basin-range faulting to between 8 and 5 Ma, during which time the Sevier Plateau was uplifted along the Sevier fault zone at least 6000 feet (2000 m). This timing is supported by $^{40}Ar/^{39}Ar$ ages of about 7 Ma for the formation of alunite and natrojarosite at Big Rock Candy Mountain, in Marysvale Canyon 35 miles (55 km) north of the map area, due to oxidation (supergene alteration) as a result of downcutting by the Sevier River to expose altered rocks in the mountain (Cunningham and others, 2005).

Pediment deposits preserved atop the Spry intrusion, about 400 feet (120 m) above Circleville Canyon immediately north of the map area (Anderson and others, 1990a), led Anderson (1987) to suggest that basin-fill deposits once filled the ancestral valley of the Sevier River to a similar depth above the modern river. However, lead-author Biek sees no evidence for such vast exhumation of late Tertiary fan alluvium in the map area. Rather, he suggests that the structural high of the Spry intrusion and its capping pediment deposits is due to an inferred fault segment boundary of the Sevier fault zone; that is, the long-term displacement rate there may be lower than that in the basins to the south and to the north. Thus, Biek interprets the capping pediment deposits simply to be remnants stranded by continued downcutting of the Sevier River as a result of differential slip on the Sevier fault, not due to exhumation of Sevier valley and Circleville Valley basin-fill deposits.

Map unit is also preserved west and south of Henderson Point immediately north of Bryce Canyon National Park. There, the deposits consist of moderately consolidated, gently west-dipping volcaniclastic sand and gravel with minor clasts of quartzite and Claron Formation limestone.

Tvf, Tvg

Upper Tertiary basin fill (Miocene) – **Fine-grained strata** (Tvf) is exposed along the valley of the Sevier River southeast of Panguitch and is light-brown, pinkish-gray, and white tuffaceous mudstone, siltstone, fine-grained sandstone, and local diatomite (Crawford, 1951); moderately to poorly consolidated; laminated to thick beds, locally with small gastropods; contains few thin beds of peloidal micritic limestone; likely deposited in small lake basins and floodplains (Moore and Straub, 1995); exposed thickness about 100 feet (30 m). **Coarse-grained strata** (Tvg) is preserved in fault blocks along the Sevier fault zone between Red and Hillsdale Canyons, and also present in nearby footwall exposures between Wilson Peak and Black Mountain; it consists of brownish-gray volcaniclastic conglomerate with pebble- to boulder-size clasts mostly of intermediate volcanic rocks but also minor basaltic clasts and rounded quartzite clasts; locally includes medium- to coarse-grained sandstone and minor mudstone; typically poorly exposed, but outcrop habit suggests that exposed parts are as much as 400 feet (120 m) thick. These basin-fill deposits are in excess of 1000 feet (300 m) thick under Sevier valley.

unconformity

Markagunt Megabreccia (lower Miocene) – Structurally chaotic assemblage of Miocene and Oligocene regional ash-flow tuff, local volcanic rock, and lesser volcaniclastic sedimentary strata that covers much of the central and northern Markagunt Plateau. Mapping and stratigraphic studies during the 1970s to 1990s show how understanding of this complex unit has evolved, as summarized by Maldonado and others (1992), Anderson (1993), Moore and Nealey (1993), Sable and Maldonado (1997a), Hatfield and others (2004, 2010), Moore and others (2004), and Rowley and others (in preparation).

Sable and Maldonado (1997a) noted that four separate rock units, listed below, have been termed megabreccia, the first three of which most workers now ascribe to other origins. The units are (1) mudflow and lava-flow breccias and fluvial volcaniclastic sedimentary rocks containing scattered megaclasts of volcanic rocks (Anderson, 1985), now known to be primary volcano-sedimentary breccia, the alluvial facies of the 23-32 Ma Mount Dutton Formation derived from the southern margin of the Marysvale volcanic field, (2) megabreccia interpreted to have resulted from collapse of high-angle fault scarps (Anderson, 1993, 2001), now known to be modern landslide deposits (Maldonado and others, 1997; Hatfield and others, 2010; Rowley and others, in preparation; see also this map), (3) megabreccia associated with the Red Hills shear zone of Maldonado and others (1989, 1992) and Maldonado (1995) that lead author Biek re-interprets as autochthonous local volcanic rocks and regional ash-flow tuffs, and (4) the principal mass of the Markagunt Megabreccia that covers much of the central and northern Markagunt Plateau, on which all workers agree. Sable and Maldonado (1997a) restricted the term to unit 4, with which we concur.

One additional unit is referred to by some workers as Markagunt Megabreccia, which lead-author Biek maps as Markagunt Megabreccia residuum (QTbx); it is well developed at the west rim of the Markagunt Plateau in and near Cedar Breaks National Monument. Hatfield and others (2004, 2010), Moore and others (2004), and Rowley and others (in preparation) interpreted this rubble as Markagunt Megabreccia, although they noted its unconsolidated nature. Following Moore (1992), lead author Biek interprets this unit to be simply the weathering product of the Markagunt Megabreccia—residuum, colluvium, landslide and collapse material, and alluvium—that is commonly present at a lower structural level along its distal southern margin.

The Markagunt Megabreccia is commonly described as consisting of house-size to city-block-size blocks, or even blocks that are as much as one square mile (2.5 km^2) in size (Sable and Maldonado, 1997a). However, we now envision the Megabreccia principally as a large sheet, several hundred square miles in extent, of mostly intact Isom Formation, large amounts of Bear Valley and Mount Dutton strata, and comparatively minor amounts of Wah Wah Springs and Brian Head Formations that has moved more or less as a coherent mass and remained mostly in proper stratigraphic order. Instructive exposures of the Megabreccia are limited so it is difficult to ascertain attitudes of individual units, but locally, upper plate strata are clearly chaotically jumbled, as at its type section along State Highway 143 northeast of Panguitch Lake and along Caddy and Butler Creeks to the north. Throughout much of its extent, formations within the

Megabreccia appear to be subparallel to the basal shear plane, but along the south margin of the Megabreccia, for example northeast of Castle Valley and at Haycock Mountain, upper plate strata are locally tilted north as exceptionally large panels as much as several square miles in extent. One way to think of the Markagunt Megabreccia is like a deck of thick cards that are sheared between one's hands—strata are intensely deformed along the shear itself, but remain relatively undisturbed in the interior of the blocks. Where the basal shear plane is not exposed and where strata are in normal straigraphic order, it is easy to mistake allochthonous for autochthonous strata, as, for example, at Haycock Mountain, described below.

The basal slip surface of the Markagunt Megabreccia generally dips gently east (mimicking the regional dip of the plateau because it was tilted with underlying strata following its emplacement) and south (because the inferred source of the Megabreccia was to the north; Sable and Maldonado, 1997a; Anderson, 2001), but at Haycock Mountain the basal slip surface dips north. The northward-dipping Isom Formation (caprock of Haycock Mountain) was reasonably interpreted by Anderson (1993) and Sable and Maldonado (1997a) as autochthonous, and they also interpreted autochthonous Isom Formation at the type area of the Megabreccia along Highway 143 east of Panguitch Lake. However, we identified a previously unreported basal conglomerate and associated clastic dikes exposed at the base of the Megabreccia on the south side of Haycock Mountain (figures 1a, 1b; 2a, 2b, and 2c). These exposures show that the entire Isom in this area is part of the gravity slide. We are uncertain if the northward dip reflects thrusting and folding in the toe of the gravity slide, or tilting due to a blind thrust fault in the underlying Claron or Brian Head Formations; moderately northwest-dipping Claron and Brian Head strata just south of Panguitch Lake suggest folding above such an inferred blind thrust fault, the westward equivalent of the Ruby's Inn thrust fault. Moderately northeast-dipping blocks near Castle Valley and Bunker Creek may simply reflect the backward tilt of jumbled, fault-bounded blocks into the basal shear plane.

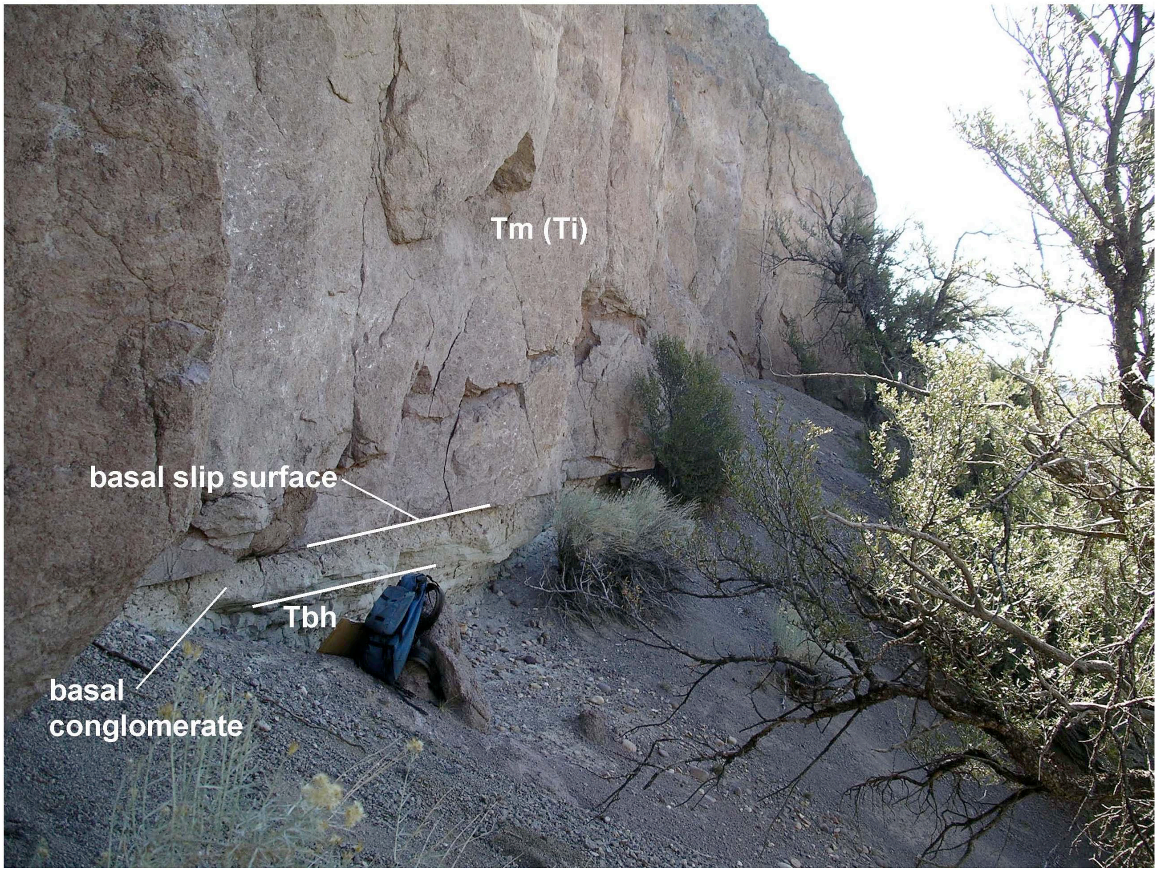

Figure 1a. Base of Markagunt Megabreccia (exposed just south of Haycock Mountain on the southwest side of hill 8652, NW1/4SE1/4 section 5, T. 36 S., R. 6 W.). Note planar slip surface (strike N. 10° W., dip 6° NE.) and underlying thin basal conglomerate, which in turn unconformably overlies similarly dipping volcaniclastic pebbly sandstone of the Brian Head Formation (Tbh). Basal conglomerate is light-reddish-brown and consists of both angular (Isom) and rounded (intermediate volcanics and quartzite) clasts floating in a well-cemented sandy matrix; the conglomerate is texturally similar to concrete or glacial till and is inferred to have been derived from pulverized Isom and underlying strata immediately above and below the detachment surface. This conglomerate is injected as dikes into the basal part of the Megabreccia, which here consists of pulverized and resilicified Isom Formation (Tm[Ti]). Pulverized Isom Formation forms a cliff 15 to 30 feet (5–10 m) high and grades abruptly upward into fractured but otherwise undisturbed Isom Formation.

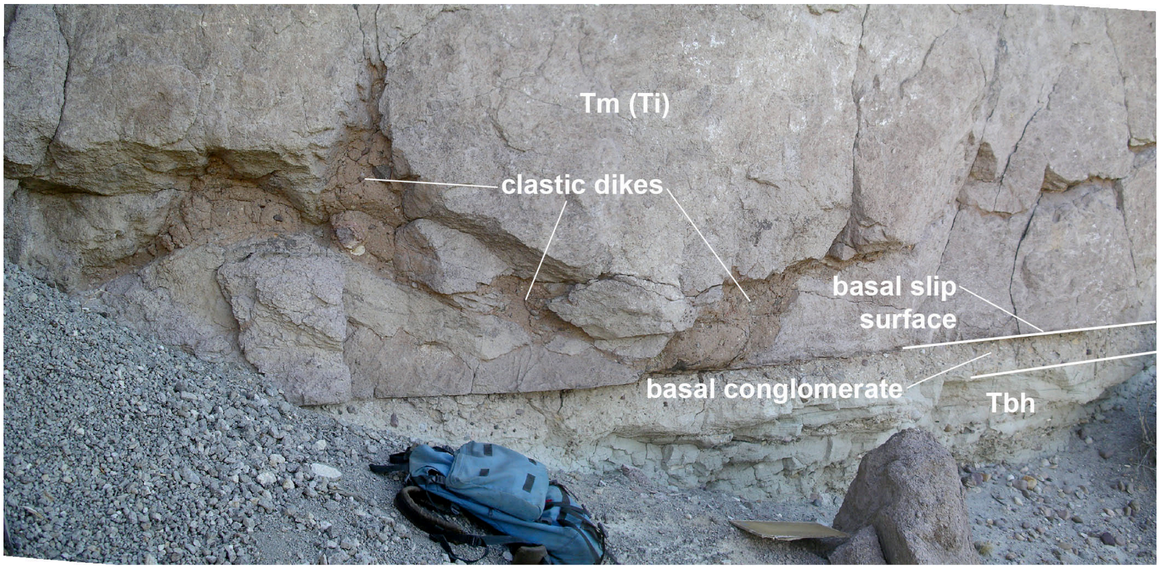

Figure 1b. Close-up of figure 1a. Note clastic dikes injected into base of Megabreccia.

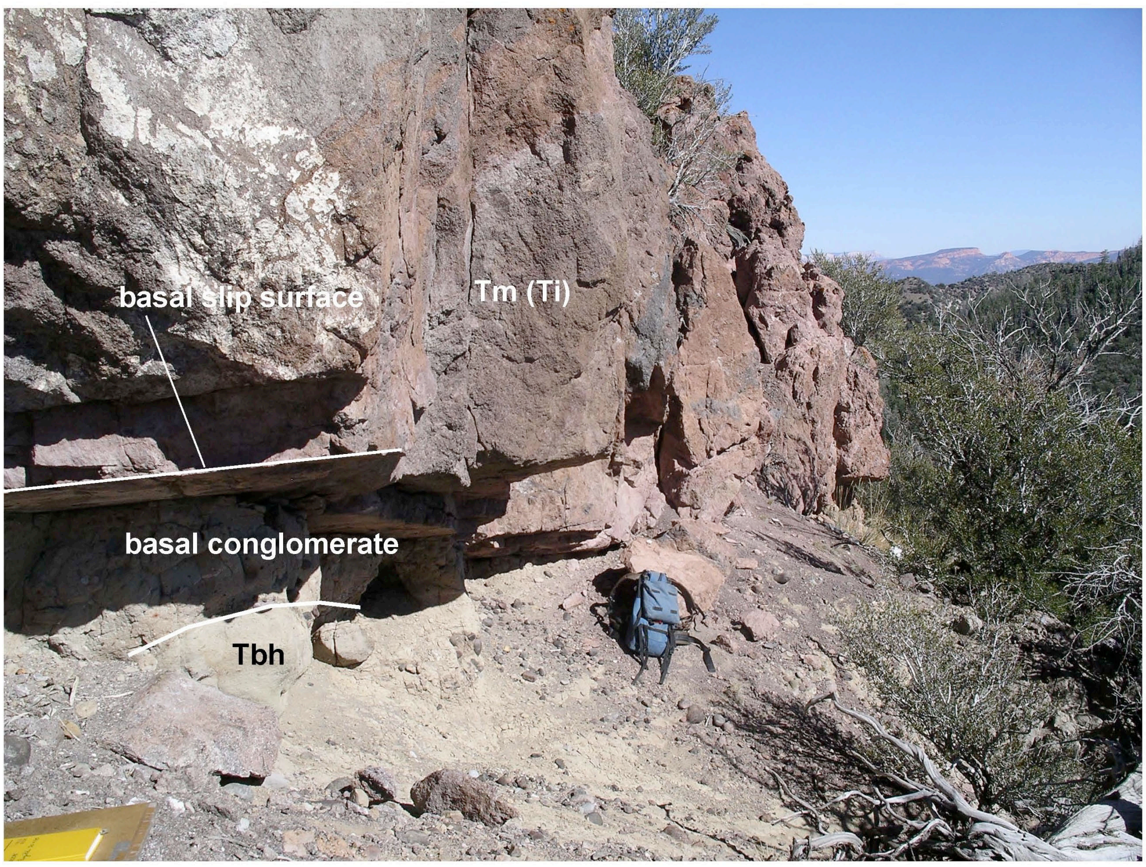

Figure 2a. Base of Markagunt Megabreccia (exposed just south of Haycock Mountain on the southeast side of an unnamed hill at the head of Little Coal Wash, NE1/4 section 6, T. 36 S., R. 6 W.). The basal part of the Megabreccia consists of about 30 feet (10 m) of brecciated, pulverized, and resilicified Isom Formation (Tm[Ti]), which grades abruptly

upward into fractured but otherwise undisturbed Isom Formation. Basal conglomerate, hidden by shadow, unconformably overlies the Brian Head Formation (Tbh).

Figure 2b. Close-up of brecciated and pulverized Isom Formation shown in figure 2a; Brunton compass for scale.

Figure 2c. Close-up of slickenlines exposed at the west side of figure 2a. Slickenlines trend 20° NW and plunge about 15°. The base of the Markagunt Megabreccia forms a planar surface that strikes N. 50° W. and dips 15° NE. Note basal conglomerate at base of Megabreccia.

Several previous workers reported slickenlines on the basal slip surface of the Megabreccia as well as roche-moutonnée-like features and tilted beds that collectively suggest southward transport. Slickenlines at the base of the Megabreccia exposed on the south side of Haycock Mountain, as well as clastic dikes and Reidel shears (see, for example, Angelier and others, 1985; Petit, 1987), also demonstrate south-southeast transport, as well as catastrophic emplacement by gravity sliding.

With our new mapping, we are able to further constrain the emplacement age of the Markagunt Megabreccia. At the premature close of the U.S. Geological Survey BARCO project in the mid 1990s, there remained disagreement as to the age and extent of the Markagunt Megabreccia as described by Anderson (2001), and an additional complication is described below. The resolution of the age and extent of the Megabreccia involves, among other issues, the Haycock Mountain Tuff in the type area of the Markagunt Megabreccia, first described in detail by Anderson (1993). Because it is undeformed, he reasoned that the Haycock Mountain Tuff ($^{40}Ar/^{39}Ar$ sanidine age of 22.75 ± 0.12 Ma, Ed Sable, U.S. Geological Survey, unpublished data, 1996) and underlying alluvial gravels are unconformable on and thus postdate the Markagunt Megabreccia, as did Rowley and others (1994a) and Hatfield and others (2010). However, Sable and Maldonado (1997a) interpreted the Haycock Mountain Tuff to be a distal facies of the Leach Canyon Formation and part of the upper plate of the Markagunt Megabreccia. Mapping in the Panguitch Lake 7.5' quadrangle, described below (see description of the Leach Canyon Formation), however, now reconfirms that the 23.8 Ma Leach Canyon Formation and 22.8 Ma Haycock Mountain Tuff are different units of slightly different age as first suggested by Anderson (1993). Thus, the interpretation of Anderson (1993, 2001), and of Rowley and others (1994a) and Hatfield and others (2010), that the Haycock Mountain Tuff represents a post-Markagunt-Megabreccia tuff that partly filled a stream channel eroded into the Megabreccia appeared eminently reasonable.

Not only is the Haycock Mountain Tuff undeformed at its type location (Anderson, 1993), the caprock of Haycock Mountain, although composed of resistant and brittle Isom Formation and overlying middle Tertiary alluvium, also appears undeformed as little as 30 feet (10 m) above the basal gravity-slide plane. Furthermore, another middle Tertiary alluvium unit that underlies the Megabreccia at Haycock Mountain contains small rounded cobbles and boulders of Isom Formation and 22.03 Ma Harmony Hills Tuff. This also demonstrates that the Isom caprock of Haycock Mountain is allochthonous, part of the upper plate of the Markagunt Megabreccia. We thus interpret the Haycock Mountain Tuff as part of the Megabreccia, having ridden largely undisturbed on the back of the resistant Isom.

The additional complication noted above involves exposures in Parowan Canyon (sections 14 and 15, T. 35 S., R. 9 W.) that were interpreted by Maldonado and Moore (1995) as 22.03 ± 0.15 Ma Harmony Hills Tuff in normal fault contact against autochthonous Isom Formation. Lead-author Biek reinterprets this Isom Formation instead to be part of the Markagunt Megabreccia that is faulted over the Harmony Hills Tuff along a gently southeast-dipping gravity-slide fault. This interpretation is consistent with evidence from Haycock Mountain described above and indicates that the Markagunt

Megabreccia was emplaced sometime after 22.03 Ma—well after emplacement of the 22.8 Ma Haycock Mountain Tuff.

To summarize, all workers agree that catastrophic emplacement of the Markagunt Megabreccia postdates the 23.8 Ma Leach Canyon Formation and most of us now agree that it also postdates the 22.8 Ma Haycock Mountain Tuff. Lead-author Biek interprets the Megabreccia as post-dating an erosional episode resulting in gravel that in turn post-dates the 22.03 Ma Harmony Hills Tuff. Therefore, the Markagunt Megabreccia appears to be younger than most workers previously envisioned. How much younger is unknown, but can nonetheless be speculated on. Because the Megabreccia is preserved in grabens at the west margin of the Markagunt Plateau, we infer that the Megabreccia predated the main phase of basin-range deformation, which resulted in the present topography and which began about 10 million years ago at this latitude (Rowley and others, 1981). The Megabreccia was thus emplaced between 10 to 22 million years ago, and likely between 20 to 22 million years ago as described below.

The Markagunt Megabreccia was interpreted by Maldonado (1995) and Sable and Maldonado (1997a) to have formed by either gravity sliding off the 20 to 21 Ma Iron Peak laccolith and associated large shallow intrusive bodies or by low-angle, thin-skinned thrusting away from the intrusions about 20 to 22 million years ago. Exposures at Haycock Mountain described above clearly show emplacement by catastrophic gravity sliding, but the trigger for the slide remains elusive. Anderson (2001) noted that the Iron Peak laccolith may be too small to have produced a dome large enough to produce the Markagunt Megabreccia, and so suggested that the Megabreccia originated from southward failure off the backslope of inferred west-northwest-striking Miocene fault blocks. However, only part of the Iron Peak laccolith is preserved in a graben. Numerous dikes are present in the horst of Claron strata immediately to the west of the laccolith; these are likely feeder dikes of the laccolith, so large parts of the laccolith must have overlain this block before being removed by erosion. An even larger laccolith could have been faulted down to the west and buried by basin-fill deposits of Parowan Valley. The Iron Peak laccolith is part of a large intrusive complex that underlies the Red Hills, northern Parowan Valley, northern Markagunt Plateau, and most of northern Sevier valley, as envisioned by interpretation of an aeromagnetic anomaly and well data by Blank and Crowley (1990), Blank and others (1992, 1998), and Rowley and others (1994). In this intrusive complex, most if not all intrusions are laccoliths (Anderson, 1965; Anderson and Rowley, 1975; Anderson and others, 1990a,b). Perhaps inflation of this larger complex, or several individual laccoliths within it, triggered formation of the Megabreccia. The 20 to 21 Ma Iron Peak laccolith is the correct age as a trigger for the Megabreccia, and an unexposed laccolith or intrusion immediately east of Upper Bear Valley is undated but could be about the same age.

Yet another possible mechanism, first suggested to lead-author Biek by volcanologist Gene Smith (University of Nevada, Las Vegas), is that the Megabreccia may have formed due to failure on oversteepened slopes that resulted from pre-caldera inflation in the Marysvale volcanic field. Calderas, however, are a relatively minor part of the Marysvale volcanic complex. The nearest calderas are about 20 miles (32 km) north of the map boundary, and of these, only the bimodal Mount Belnap caldera 25 miles (40 km) north of the map boundary has an age of 21 Ma (Rowley and others, 2002) that is reasonable as a trigger based on what we know about the timing of gravity sliding of the Markagunt Megabreccia (Rowley and others 2002, 2005). Thus, we have several possibilities but lack a definitive trigger for the formation of the Markagunt Megabreccia. Of the possibilities, gravity sliding off the Iron Peak laccolith seems the most likely. Mapping in the Iron Springs mining district west of Cedar City, where a complex of laccoliths produced many large gravity slides comparable to that which produced the Markagunt Megabreccia (Hacker, 1998; Hacker and others, 2002; Rowley and others, 2006), lends support to this hypothesis.

Interestingly, as noted by Sable and Maldonado (1997a) and by Davis (1997a,b), the south margin of the Markagunt Megabreccia is on trend with well documented, east-trending, south-vergent thrust faults, including the Rubys Inn thrust fault, involving Upper Cretaceous and Paleocene-Eocene Claron Formation on the Paunsaugunt Plateau. These thrust faults are interpreted to represent gravitational loading and collapse of the southern part of the Marysvale volcanic field (or possibly coeval batholithic emplacement) (Davis and Krantz, 1986; Lundin, 1989; Davis and Rowley, 1993; Merle and others, 1993; Davis, 1999). In the "two-tiered" model of Davis (1997a and b, 1999), the Markagunt Megabreccia is but one structure—an upper-level part—of a second, deeper series of Tertiary thrusts directed outward from the southern Marysvale volcanic field, which spread and collapsed under its own weight, resulting in southward-directed thrust faults rooted in evaporite strata of the Middle Jurassic Carmel Formation. On the Markagunt Plateau, gently northwest-dipping Claron and Brian Head strata south of Panguitch Lake, and gently north-dipping Isom Formation at Haycock Mountain, may reflect folding in the upper plate of an east-trending, south-vergent, blind thrust fault, the westward continuation of the Rubys Inn thrust fault.

The northern extent of the Megabreccia is unknown, but it probably does not extend north of the latitude of the Iron Peak intrusion; it is not recognized in the Beaver 30´ x 60´ quadrangle to the north (Rowley and others, 2005). Because the Isom Formation in the north-central Markagunt Plateau, east and north of the Iron Peak intrusion, is comparatively thin, and because the Isom is typically thick where it is part of the Megabreccia, it appears that the breakaway fault(s) must be south of the intrusion.

Tm **Markagunt Megabreccia, undivided** – The Markagunt Megabreccia is undivided where exposures are insufficient to delineate bedrock units at the map scale and in more remote areas due to time constraints; Tm also denotes a basal conglomerate as much as several tens of feet thick and associated clastic dikes, and minor Brian Head Formation, at the base of the Megabreccia at Flake Mountain. Most areas mapped as Tm consist predominantly of the Isom Formation (which is typically pervasively and finely fractured so that it weathers to grussy soils and rounded hills), but locally includes Wah Wah Springs and Brian Head strata, and, north of Panguitch Lake, large amounts of block and ash-flow tuff, volcaniclastic sandstone, and minor pebbly conglomerate of the Bear Valley and Mount Dutton Formations. On top of the Markagunt Plateau, north of the latitude of Panguitch Lake, Tm was emplaced on the resistant, planar, gently east-dipping surface of the Isom Formation, but south of the lake it was emplaced on the Leach Canyon Formation. The northward extent of the Megabreccia is uncertain and it is unknown if Bear Valley and Mount Dutton strata in the north-central part of the map area are autochthonous or allochthonous. At the west edge of the plateau, south of Iron Peak, it was emplaced on Brian Head strata. The Markagunt Megabreccia locally exceeds 500 feet (150 m) thick.

Tm(Thm) **Markagunt Megabreccia, Haycock Mountain Tuff component** – Consists of two cooling units at its type section along Panguitch Creek east of Panguitch Lake: lower unit is white to very light pink, unwelded, crystal-poor rhyolite tuff that is overlain by light-pink, unwelded, moderately resistant crystal-poor rhyolite tuff; both contain common pumice fragments and lithic fragments of black, aphanatic, mafic volcanic rock; typically forms moderately resistant ledge over undeformed volcaniclastic conglomerate [Tm(Ta)] and elsewhere overlies locally deformed Bear Valley Formation [Tm(Tbv)] and Mount Dutton Formation [Tm(Td)]; mapped north of Haycock Mountain where it is about 35 feet (11 m) thick.

The Haycock Mountain Tuff is petrographically and chemically similar to the Leach Canyon Formation, but lacks red lithic fragments that characterize the Leach Canyon Formation (see the Leach Canyon Formation unit description for details). As noted by Hatfield and others (2010), the Haycock Mountain Tuff yielded an $^{40}Ar/^{39}Ar$ age of 22.75 ± 0.12 Ma (Ed Sable, U.S. Geological Survey, unpublished data, 1996). On the basis of the undeformed nature of the Haycock Mountain Tuff and its underlying conglomerate, Anderson (1993), Rowley and others (1994a), and Hatfield and others (2010) interpreted the Haycock Mountain Tuff to postdate emplacement of the Markagunt Megabreccia. New mapping on the south flank of Haycock Mountain, including the recognition of a post-22.03 Ma conglomerate beneath the Markagunt Megabreccia slide plane, indicates that the Haycock Mountain Tuff was transported largely undisturbed in the upper plate of the Megabreccia. Similarly, other units included within the Markagunt Megabreccia are locally largely undisturbed except near its gravity slide fault.

Rowley and others (1994a) reported a K-Ar age on plagioclase of 22.3 ± 1.1 Ma (their sample 89USA2A) for what they then interpreted to be the basal vitrophyre of Haycock Mountain Tuff at the southwest side of Haycock Mountain. However, this vitrophyre underlies the Markagunt Megabreccia, is chemically a trachydacite (although apparently weathered with a large LOI on analysis), and yielded an $^{40}Ar/^{39}Ar$ plagioclase age of 24.23 ± 0.17 Ma (Sable and Maldonado, 1997a). The vitrophyre is overlain by an unwelded, light-brownish-gray ash-flow tuff, also chemically a trachydacite (figures 3a, 3b). We are uncertain how to correlate this vitrophyre and associated ash-flow tuff—probably a local ash-flow tuff—but it appears certain that it cannot be the Haycock Mountain Tuff; Rowley (in Hatfield and others, 2010) re-interpreted it to be an older (pre-Markagunt Megabreccia) Bear Valley rhyolitic tuff.

Figure 3a. View northwest to the southwest part of Haycock Mountain. Note light-colored ash-flow tuff and underlying basal vitrophyre near the top of the mountain, shown in more detail in figure 3b. Volcaniclastic strata of the Brian Head Formation (Tbh) are in the foreground; "caprock" of Haycock Mountain, above the light-colored ash-flow tuff, is the Isom Formation.

Figure 3b. View northeast to basal vitrophyre and associated ash-flow tuff on the southwest side of Haycock Mountain; note underlying reddish-brown conglomerate (Ta), which consists of rounded, pebble- to boulder-size clasts of intermediate volcanic rocks and quartzite that here is about 100 feet (30 m) thick. The vitrophyre is about 20 feet (6 m) thick and is marked by a thin brick-red band at its top. It is overlain by a similar thickness of unwelded light-brown ash-flow tuff; chemically, both the vitrophyre and unwelded tuff are trachydacite. This vitrophyre yielded a K-Ar age on plagioclase of 22.3 ± 1.1 Ma (Rowley and

others, 1994a; their sample 89USA2A) and an $^{40}Ar/^{39}Ar$ plagioclase age of 24.23 ± 0.17 Ma on the same sample (Sable and Maldonado, 1997a). We are uncertain how to correlate this vitrophyre and associated ash-flow tuff —probably a local ash-flow tuff—but it appears certain that it cannot be the Haycock Mountain Tuff; Rowley (in Hatfield and others, 2010) re-interpreted it to be an older (pre-Markagunt Megabreccia) Bear Valley rhyolitic tuff.

Tm(Td) **Markagunt Megabreccia, Mount Dutton Formation, alluvial facies component** – Brown or locally reddish-brown volcanic mudflow breccia of mostly andesitic composition, volcaniclastic pebble to boulder conglomerate, and minor tuffaceous sandstone; interpreted to be part of the Markagunt Megabreccia, although it may contain strata that postdate emplacement of the Megabreccia; maximum thickness in the map area is probably at least 600 feet (250 m).

Tm(Ta) **Markagunt Megabreccia, middle Tertiary alluvium component –** Volcaniclastic conglomerate and pebbly sandstone on the north flank of Haycock Mountain and area to the north; contains quartzite cobbles and small boulders in the basal part of the deposits; typically forms cobble-covered hillsides, but is locally well-consolidated in exposures on the southwest side of Haycock Mountain; as mapped here, the unit [Tm(Ta)] at Haycock Mountain overlies and is in turn locally overlain by the Isom Formation component [Tm(Ti)], all interpreted to be part of the upper plate of the Markagunt Megabreccia; additionally, this alluvium component is as much as 800 feet (250 m) above Panguitch Creek and the type section of Haycock Mountain Tuff, thus to have postdated emplacement and tilting of the Megabreccia as inferred by Anderson (1993), the alluvium we map as [Tm(Ta)] would have had to completely fill the ancestral Panguitch Creek drainage and then been exhumed, but we see no compelling evidence for this interpretation; maximum thickness in this area is probably about 100 feet (30 m).

Tm(Tdbv) **Markagunt Megabreccia, Mount Dutton and Bear Valley components, undivided** – Mapped north of Panguitch Lake where exposures are typically inadequate to readily differentiate these formations; exceeds 500 feet (150 m) thick.

Tm(Tbv) **Markagunt Megabreccia, Bear Valley component** – White to light-gray, moderately to well-sorted, fine- to medium-grained volcaniclastic sandstone having high-angle cross-beds, and similarly colored tuffaceous mudstone and siltstone; typically pervasively deformed along shears and by small folds. Map unit includes white, unwelded, massive rhyolitic ash-flow tuff that contains common pebble-size lithic fragments of intermediate volcanic rocks and rounded quartzite pebbles. As much as several hundred feet thick.

Tm(Tdm) **Markagunt Megabreccia, Mount Dutton Formation, mafic alluvial facies component** – Dark-gray, vesicular, basaltic andesite and basalt present as angular cobble- to boulder-size blocks floating in a light-gray sandy and muddy matrix of the same composition; monolithic; a small area of basaltic scoria, possibly a primary rafted block, is present north of Bunker Creek in the NE1/4NE1/4 section 12, T. 36 S., R. 8 W., about 3 miles (5 km) west of Panguitch Lake; maximum thickness is about 80 feet (24 m).

Mapped between Panguitch Lake and Sidney Peaks where it unconformably overlies 24 Ma Leach Canyon Formation (Tql), and north of Panguitch Lake, where it overlies the Isom Formation. In the Bunker Creek drainage west of Panguitch Lake, the map unit is overlain by Isom Formation or locally by Wah Wah Springs Formation, each as part of the Markagunt Megabreccia. Exposures north of Bunker Creek (in the north-central part of section 12, T. 36 S., R. 8 W., about 3 miles [5 km] west of Panguitch Lake) show 30 feet (9 m) of paleotopography cut into the upper surface of the Leach Canyon, with blocks of Leach Canyon incorporated into the base of the overlying volcanic mudflow breccia. It is unclear if the deposits between Panguitch Lake and Sidney Peaks (on the west rim of the Markagunt Plateau northeast of Brian Head peak) partly underlie or are everywhere part of the Megabreccia; for simplicity, they are mapped here as part of the Megabreccia.

Tm(Ti) **Markagunt Megabreccia, Isom Formation component** – Medium-gray, crystal-poor, densely welded, trachydacitic ash-flow tuff; small (1–3 mm) euhedral crystals constitute 15 to 20% of the rock and are mostly plagioclase (90%) and minor pyroxene, magnetite, and quartz set in a devitrified glassy groundmass; most outcrops and blocks weather to grussy soils and rounded hills; except at Haycock Mountain, rarely forms cliffs as is typical of the autochthonous Isom Formation; maximum thickness about 400 feet (120 m).

Although generally poorly exposed, Isom constitutes the great bulk of the Megabreccia mapped along its southern margin, roughly between Haycock Mountain, Brian Head, and Horse Valley, and in down-faulted blocks at the plateau's west margin. This map unit locally includes areas of Brian Head Formation, Wah Wah Springs Formation, and volcanic mudflow breccia that are difficult to delineate given extensive forest cover and inconspicuous outcrop habit. It generally is faulted over the Leach Canyon Formation west of Panguitch Lake, faulted over Isom Formation north of Panguitch Lake, and faulted over thin lower Miocene conglomerate that unconformably overlies the Brian Head Formation east of Panguitch Lake.

Tm(Tnw) **Markagunt Megabreccia, Wah Wah Springs Formation component** – Pale-red, grayish-orange-pink, and pale-red-purple, crystal-rich, moderately welded, dacitic ash-flow tuff; phenocrysts of plagioclase, hornblende, biotite, and quartz (with minor Fe-Ti oxides and sanidine) comprise about 40% of the rock; mapped about 5 miles (8 km) west and west-southwest of Panguitch Lake, where it rests on displaced Brian Head strata [Tm(Tbhv)] northeast of Castle Valley, and in the upper reaches of Bunker Creek, where it rests on displaced Isom Formation [Tm(Ti)] or displaced volcanic mudflow breccia (Tm[Tdm]); about 40 feet (12 m) thick.

Tm(Tbh) **Markagunt Megabreccia, Brian Head Formation component** – Poorly exposed, but distinctive white to light-gray volcaniclastic mudstone, pebbly sandstone, micritic limestone, and chalcedony are present in colluvium, thus betraying the formation's presence northeast of Castle Valley (about 5 miles [8 km] west-southwest of Panguitch Lake) where it rests out-of-sequence on autochthonous Leach Canyon Formation; on the ridge at the common border of sections 9 and 16, T. 36 S., R. 8 W., pebbly volcaniclastic sandstone of the Brian Head Formation is well exposed at the head of a landslide, dips about 25° northeast, and is overlain by similarly dipping Wah Wah Springs Formation; on the hill to the south, however, Brian Head strata appear to be subhorizontal; thickness uncertain but outcrop patterns suggest that displaced Brian Head strata likely exceed 100 feet (30 m) thick.

Also present on the southeast side of Haycock Mountain and the north side of Flake Mountain, where white and light-gray, locally tuffaceous, volcaniclastic sandstone, pebbly sandstone, mudstone, minor tuffaceous limestone, and local multi-hued chalcedony are faulted and folded, indicative of deformation as part of the Markagunt Megabreccia (on the south side of Haycock Mountain, deformation may be due to south-vergent thrust faulting associated with the westward extension of the Ruby Inn thrust); exposed thickness at Haycock Mountain as much as 150 feet (45 m), but only about 40 feet (12 m) thick at Flake Mountain.

Ta **Miocene alluvium** (lower Miocene) – Moderately sorted, moderately consolidated, pebble to boulder gravel mapped at the southeast end of Flake Mountain and on the south side of Haycock Mountain; contains rounded volcanic clasts and lesser quartzite and Claron Formation limestone clasts; on the south side of Haycock Mountain, the Markagunt Megabreccia is emplaced onto the map unit, and the map unit includes rounded clasts of Isom Formation and Harmony Hills Tuff; maximum exposed thickness about 80 feet (25 m).

Also consists of high-level alluvial deposits in the southwest corner of the map area at Miners Peak, where it is about 90 feet (27 m) of unconsolidated, poorly sorted, clay- to very large boulder-size sediment characterized by large quartz monzonite boulders. Quartz monzonite boulders as much as about 30 feet (10 m) in diameter constitute about 90% of the deposits. Clasts also include large boulders of Claron Formation limestone to 18 feet (6 m) long, recycled, rounded pebbles and small cobbles of Precambrian and Cambrian quartzite, lesser Cretaceous sandstone boulders, and rare cobbles and boulders of pebbly sandstone of uncertain origin. Except for the quartzite, most clasts are subangular to subrounded. Probably deposited by debris flows originating in the ancestral Pine Valley Mountains (see Biek and others [2009] for a discussion of the provenance and age of these unusual deposits).

Tl **Limerock Canyon Formation** (lower Miocene) – White, light-gray, and pale- to olive-green, tuffaceous, volcaniclastic sandstone, pebbly sandstone, gritstone, pebbly conglomerate, mudstone, and minor tuffaceous limestone; commonly bioturbated; includes at least 10 thin beds of ash-fall tuff; clasts are about 90% volcanic but include as much as 10% quartzite and sandstone; Kurlich and Anderson (1997) stated that the formation lacks Needles Range, Isom, Bear Valley, and Mount Dutton clasts, but most clasts appear to lead-author Biek to be Isom; unconformably overlain by unconsolidated upper Tertiary fan alluvium (Taf); as much as 290 feet (88 m) thick in a composite type section west of Hatch (Kurlich, 1990; Kurlich and Anderson, 1997).

The Limerock Canyon Formation was deposited in fluvial and minor lacustrine environments (Kurlich and Anderson, 1997). It is present only on the east part of the Markagunt Plateau near Hatch, south of the Markagunt Megabreccia, where it appears to cut out much of the Brian Head Formation, and where it may be preserved in a subtle basin in front of an inferred blind west-trending thrust fault (the inferred westward continuation of the Ruby's Inn thrust fault). Two ash-fall tuff beds, about 100 feet (30 m) and 200 feet (60 m) above the base of the formation at the type section west of Hatch, respectively, yielded K-Ar ages of 21.5 ± 0.6 Ma (biotite) and 21.0 ± 1.0 Ma (sanidine), and of 20.2 ± 1.4 Ma (biotite) and 19.8 ± 0.8 Ma (sanidine) (Sable and Maldonado, 1997b); Sable and Maldonado (1997b) also reported an $^{40}Ar/^{39}Ar$ age of 20.48 ± 0.8 Ma (biotite) and 21.0 ± 1.0 Ma (sanidine), and we obtained a U-Pb age on zircon from an airfall tuff near the middle of the formation of 20.52 ± 0.49 Ma.

Sable and Maldonado (1997b) described the difficulty of differentiating similar volcaniclastic strata of the Limerock Canyon, Bear Valley, and Brian Head Formations. The type section of the Limerock Canyon Formation (west of Hatch) contains a few tens of feet of strata that we tentatively reassign to the Brian Head Formation, and we interpret that the limestone that Kurlich and Anderson (1997) assigned to the Brian Head Formation at the base of this type section is in fact the upper white member of the Claron Formation as originally described by Kurlich (1990).

Tip **Iron Peak laccolith** (lower Miocene) – Medium-gray gabbro-diorite porphyry composed almost entirely of augite and plagioclase (calcic labradorite) and about 8% opaque oxide minerals, mostly magnetite, with diorite the dominant phase (Anderson, 1965; Spurney, 1984); magnetite veins are present throughout the intrusion and are as much as 10 feet (3 m) in width, but most are less than one inch (2.5 cm) wide (Spurney, 1984); base of laccolith is well exposed in the north canyon wall of Little Creek, northeast of Paragonah, which has incised through the laccolith to reveal numerous feeder dikes; originally referred to as the Iron Point laccolith by Anderson (1965) and Anderson and Rowley (1975), as the namesake peak was then known (the peak was renamed and is now referred to as Iron Peak); yielded K-Ar whole-rock age (corrected according to Dalrymple, 1979) of 20.2 ± 0.5 Ma (Fleck and others, 1975); exposed thickness is as much as about 800 feet (240 m).

Iron Peak forms the easternmost laccolith of the Iron Axis, a northeast-trending belt of early Miocene calc-alkaline laccoliths and concordant stocks that rose at about 22 to 20 Ma above the roof of an inferred large batholith (Blank and Mackin, 1967; Cook and Hardman, 1967; Rowley, 1998; Rowley and others, 1998). Iron Peak is the second youngest and most mafic of the Iron Axis intrusions. Most of the other plutons of the Iron Axis are of quartz monzonite porphyry and appear to be partly controlled by northeast-striking, southeast-verging Sevier-age thrust faults; they were emplaced at shallow depths, mostly within about 1.2 miles (2 km) of the surface (Mackin and others, 1976; Van Kooten, 1988; Hacker and others, 2002, 2007; Rowley and others, 2006). Like the other laccoliths in the belt, the Iron Peak laccolith probably formed rapidly following a two-stage emplacement process—injection of a sill immediately followed by inflation—at shallow crustal depth of less than 4000 feet (1.2 km) based on stratigraphic reconstructions (Spurney, 1984; see also Hacker and others, 2002, 2007; Willis, 2002). Rapid inflation and doming of most laccoliths of the Iron Axis led to their partial unroofing by gravity sliding, immediately followed by volcanic eruptions (Mackin, 1960; Blank and Mackin, 1967; Hacker and others, 1996, 2002, 2007; Hacker, 1998; Willis, 2002; Rowley and others, 2006). Spurney (1984) interpreted exposures immediately east of the Iron Peak laccolith as a peripheral breccia complex; Maldonado and others (2011) reinterpreted this area as older Bear Valley breccia (Tbvb), but we tentatively map the area as lava flows derived from the Iron Peak intrusion. Spurney (1984) also described volcanic rocks of similar composition to the south on the divide between Red Creek and Little Creek canyons, northeast of Paragonah, that we map as lava flows (Tipl) associated with the Iron Peak laccolith. A lava flow within volcanic mudflow breccias yielded a K-Ar age of 21.2 ± 0.5 Ma (Fleck and others, 1975; sample R-27; corrected according to Dalrymple, 1979) that was interpreted by Anderson and Rowley (1975, p. 28) and Rowley and others (1994, p. 12) to be derived from eruption of the Iron Peak laccolith; however, coordinates reported by Fleck and others (1975) for the latter sample are probably incorrect—that sample location falls on Isom Formation on the west side of Ipson Creek about 3 miles (5 km) northwest of Panguitch Lake.

The Iron Peak laccolith was previously mapped as intruding the Brian Head Formation (Spurney, 1984; Maldonado and others, 2011), but our preliminary mapping suggests that it intruded both Brian Head volcaniclastic strata and Bear Valley ash-flow tuff that are juxtaposed across a pre-Iron Peak-intrusion graben now preserved at the west edge of the Markagunt Plateau, about 5 miles (8 km) northeast of Paragonah. We plan additional mapping to delineate the extent of the laccolith and its host strata.

Emplacement and doming of the Iron Peak laccolith was suggested as one possible cause of sliding of the Markagunt Megabreccia (Sable and Maldonado, 1997a) and this remains the most likely option, although Anderson (1993, 2001) suggested that the intrusion seemed too small to have produced such a large gravity slide. However, because the laccolith is only exposed in a graben, we do not know its original extent, particularly how far west it may have once reached. Based on the presence of apparent feeder dikes (Tipd) in the Claron horst west of Iron Peak, we infer that the laccolith extends west into the subsurface of Parowan Valley and thus may indeed be large enough to have triggered the gravity slide.

Spurney (1982, 1984) suggested that magnetite veins formed late in the laccolith's emplacement, a result of alteration of augite phenocrysts. While magnetite veins are common, they are apparently of insufficient number to have been of economic importance, unlike the nearby Iron Springs mining district west of Cedar City, the largest iron-producing district in the western U.S. (Mackin, 1947, 1954, 1960, 1968; Blank and Mackin, 1967; Bullock, 1970; Mackin and others, 1976; Mackin and Rowley, 1976; Rowley and Barker, 1978; Barker, 1995; Rowley and others, 2006).

Tipl **Lava flows associated with the Iron Peak laccolith** (lower Miocene) – Mafic lava flows preserved south and east of the Iron Peak laccolith and tentatively inferred to represent eruptive products of laccolith emplacement; thickness uncertain, but likely in excess of several hundred feet thick.

Tipd **Feeder dikes of Iron Peak laccolith** (lower Miocene) – Mafic dikes exposed in the north canyon wall of Little Creek, immediately south of the Iron Peak laccolith; of the same composition as the adjacent laccolith, and so are interpreted to be its feeder dikes (Anderson, 1965; Spurney, 1984; Hacker and others, 2007); dikes intruded Brian Head Formation, which early workers then called the upper part of the Claron Formation, and are resistant and so stand as tall fins; most dikes trend northeast, dip moderately to steeply west, and most are about 6 feet (2 m) wide but range from about 0.8 to 25 feet (0.25–8 m) wide.

Timd **Mafic dikes at the west edge of the Markagunt Plateau** (lower Miocene) – Highly altered, greenish-gray to brownish-gray, aphanitic to fine-grained mafic dikes that trend mostly north in the Cottonwood Mountain quadrangle northeast of Paragonah; some dikes contain small plagioclase phenocrysts; typically deeply weathered and so poorly exposed, but most dikes fill joints and small-displacement faults, which are especially well developed in a horst of gently northwest-tilted Claron strata at the west edge of the plateau, west of Iron Peak (the bar and ball symbol on these dikes indicates relative sense of displacement of the fault); a sample from one of the northwest-trending dikes west of the Iron Peak laccolith yielded a K-Ar age of about 20 Ma (H.H. Mehnert and R.E. Anderson, written communication to F. Maldonado, 1988), consistent with an interpretation that the dikes are related to the laccolith; dikes range from about 1 to 20 feet (0.3–6 m) wide.

Also used to denote basaltic and andesitic dikes in the adjacent Little Creek Peak quadrangle to the east, which Anderson and others (1987) interpreted as feeder dikes for the Mountain Dutton and Bear Valley Formations.

To **Osiris Tuff** (lower Miocene to upper Oligocene) – Resistant, pink to orange, reddish- and grayish-brown, and light-gray, densely welded, moderately crystal rich, rhyodacitic ash-flow tuff; contains about 20 to 25% phenocrysts of plagioclase, subordinate sanidine, and minor biotite, pyroxene, and Fe-Ti oxides (Anderson and Rowley, 1975; Rowley and others, 1987); forms a simple cooling unit, which in some places includes an upper, light-gray vapor-phase zone and a basal black vitrophyre as much as 10 feet (3 m) thick; commonly weathers to rounded boulders; contains drawn out pumice lenticles; upper part locally contains steeply dipping flow foliations, rheomorphic features caused by secondary flowage of rock during the last few tens of meters of movement; caps the Mount Dutton Formation in the northeast corner of the map area, and also caps the Escalante Mountains immediately east of the map area (Doelling and Willis, 1999); the preferred age of the Osiris is about 23 Ma (Rowley and others, 1994a); maximum thickness in this map area is about 30 feet (10 m).

The Osiris Tuff is virtually identical in lithology, petrology, and isotopic age to the Bauers Tuff Member of the Condor Canyon Formation (Rowley and others, 1994a). The Osiris Tuff erupted from the Monroe Peak caldera, about 30 miles (50 km) north of the map area, which is the largest caldera of the Marysvale Volcanic Field and the youngest of the calc-alkaline sequence (Rowley and others, 1981; Steven and others, 1984). The Osiris is one of the most widespread ash-flow tuffs of the Marysvale Volcanic Field (Rowley and others, 1994a) and has an estimated volume of 60 cubic miles (250 km^3) including a thick intracaldera fill (Cunningham and others, 2007). Cunningham and others (2007) reported that it erupted between 22.92 and 22.81 Ma based on preliminary $^{40}Ar/^{39}Ar$ ages, and Fleck and others (1975) reported K-Ar ages (corrected according to Dalrymple, 1979) on biotite of 23.4 ± 0.4 Ma from the southern Sevier Plateau immediately north of the map area, 22.7 ± 0.4 Ma from the southern Tushar Mountains north of the map area, and 22.9 ± 0.4 Ma from the Wasatch Plateau. An additional age of 23.0 ± 0.4 Ma attributed to the Osiris Tuff is actually a lava flow from the vent facies of the Mount Dutton Formation.

Tdli **Mount Dutton Formation, Leach Canyon Formation, and Isom Formation, undivided** (lower Miocene to upper Oligocene) – Poorly exposed, complexly faulted outcrops of these units at Long Hill, in the northwest Red Hills, interpreted by Maldonado and Williams (1993a) as part of the upper plate of their Red Hills shear zone.

Td **Mount Dutton Formation, alluvial facies** (upper Oligocene) – Light- to dark-gray and brown, andesitic to dacitic volcanic mudflow breccia and lesser interbedded volcaniclastic conglomerate and tuffaceous sandstone; also contains subordinate lava flows, flow breccia, and minor felsic tuff; Anderson and Rowley (1975) defined the Mount Dutton Formation as consisting of most of the rocks exposed on the south flank of the Marysvale volcanic pile, and divided it into complexly interfingering and cross-cutting vent and alluvial facies derived from clustered stratovolcanoes and dikes that form most of the southern Marysvale volcanic field; except for the Kingston Canyon Tuff Member, only those rocks associated with the alluvial facies are present in the map area, where they typically overlie the Bear Valley Formation on the Markagunt Plateau and the Brian Head Formation on the Sevier Plateau.

The Marysvale volcanic field is one of several voluminous calc-alkaline, subduction-related volcanic centers and underlying source plutons that characterized the West from Oligocene to Miocene time at this latitude (Lipman and others, 1972; Rowley and Dixon, 2001). Fleck and others (1975) and Rowley and others (1994a) reported several K-Ar ages of 23 to 30 Ma on rocks of the coeval vent facies, not including an anomalously young age (corrected according to Dalrymple, 1979) of 21.2 ± 0.5 Ma (sample R-27 of Fleck and others, 1975) ascribed by Anderson and Rowley (1975, p. 28) and Rowley and others (1994a) to a local volcano, perhaps from the Iron Peak intrusion east of Paragonah. The alluvial facies is at least 1000 feet (300 m) thick in the map area in the northern Markagunt Plateau (Anderson and Rowley, 1987) and is at least 6000 feet (2000 m) thick farther north (Anderson and others, 1990a, 1990b; Rowley and others, 2005). It pinches out radially from an east-trending string of stratovolcanoes along the southern part of the Marysvale volcanic field.

Tds **Mount Dutton Formation, local sandstone facies** (upper Oligocene) – Pale- to dark-gray and light-yellowish-brown, cross-bedded, slope-forming, zeolite-cemented tuffaceous sandstone; present at the northern edge of the map area, about 4 miles (6 km) northwest of Bear Valley Junction; as much as about 100 feet (30 m) thick.

Tdk **Kingston Canyon Tuff Member** (upper Oligocene) – Reddish-brown and pink densely welded trachytic ash-flow tuff characterized by a thin basal black vitrophyre, local steeply dipping flow foliation, and light-gray "lenticules," gas bubbles drawn out as much as 3 feet (1 m) in the plane of bedding yet only an inch (2.5 cm) or less thick; forms a single cooling unit with pumice lenticules and sparse to moderately abundant volcanic rock fragments; phenocrysts are plagioclase and minor pyroxene, Fe-Ti oxides, and biotite; basal vitrophyre as much as 6 feet (2 m) thick is locally exposed; present in the southern Sevier Plateau where it pinches out against paleotopography near the base of the Mount Dutton Formation (Anderson and Rowley, 1975; Rowley and others, 1987, 1994); Fleck and others (1975) determined a K-Ar age on biotite from the unit of 25.1 ± 0.4 Ma, as discussed by Anderson and Rowley (1975); maximum thickness about 30 feet (10 m).

Tbv **Bear Valley Formation, undivided** (upper Oligocene) – Volcaniclastic sandstone and, especially in the upper part of the formation, lesser interbedded lava flows, volcanic mudflow breccia, conglomerate, mudstone, and ash-fall and ash-flow tuff beds; sandstone is white to light gray, greenish gray, yellowish gray, olive gray, and locally quite vivid green, typically poorly indurated, moderately to well-sorted, and fine to medium grained; sand is about 60% quartz, and the remainder is feldspar, biotite, hornblende, augite, and relict pumice replaced by zeolite; cement is mostly zeolite (clinoptilolite, commonly altered to chlorite) (Anderson, 1971); most sandstone is characterized by high-angle cross-beds indicative of eolian deposition; Fleck and others (1975) reported two K-Ar ages (corrected according to Dalrymple, 1979) of 24.6 ± 0.4 Ma and 24.5 ± 0.5 Ma from the upper part of the formation in the Fivemile Pass quadrangle, west of Panguitch; the formation is in excess of 1000 feet (300 m) thick at its type section on the northern Markagunt Plateau (north of Highway 20 and about 1.5 miles [2.5 km] west of its junction with U.S. Highway 89; Anderson, 1971), but is typically 500 to 800 feet (150–200 m) thick (Anderson and Rowley, 1987); the unit is as much as about 260 feet (80 m) thick in the Red Hills (Maldonado and Williams, 1993b).

Sand was derived from the south and west and accumulated in a low-relief basin bounded on the north by an east-trending fault scarp possibly associated with the 26 Ma Spry intrusion (Anderson, 1971; Anderson and others, 1990a, 1990b). Anderson and others (1987) described the difficulty of differentiating similar lava flows and mudflow breccias of the Bear Valley and overlying Mount Dutton Formations. Kaufman and Anderson (1981) reported a possible vent for the volcanic rocks in the formation near Twin Peaks, about 7 miles (11 km) north of Panguitch Lake, but this area appears to be part of the Markagunt Megabreccia and it is uncertain if some or all of the deformation observed there resulted from megabreccia emplacement or is associated with a small caldera. Green sandstone was locally quarried from Bear Valley strata about 4 miles (6 km) southwest of Bear Valley Junction (Anderson and Rowley, 1987).

Tbvb **Bear Valley Formation, mudflow breccia unit** (upper Oligocene) – Pale-yellowish-brown breccia composed of pebble- to cobble-size clasts, mostly of intermediate-composition volcanic rocks and lesser amounts of tuff and tuffaceous sandstone; as much as about 800 feet (245 m) thick south of Cottonwood Mountain, about 7 miles (11 km) northeast of Paragonah.

Tbvv **Bear Valley Formation, lava flows and mudflow breccia unit** (upper Oligocene) – Dark-gray basaltic(?) lava and mudflow breccia mapped east of Upper Bear Valley in the Little Creek Peak quadrangle; interpreted by Anderson and others (1987) to be the remnants of a small stratovolcano, a local vent complex of the Bear Valley Formation.

Quichapa Group (lower Miocene to upper Oligocene) – Consists of three regionally distinctive ash-flow tuffs: in ascending order, the Leach Canyon Formation, Condor Canyon Formation, and Harmony Hills Tuff (Mackin, 1960; Williams, 1967; Anderson and Rowley, 1975; Rowley and others, 1995). The Leach Canyon Formation likely erupted from the Caliente caldera complex (Williams, 1967), the two-member Condor Canyon Formation clearly erupted at least in part from the west (Clover Creek caldera) part of the Caliente caldera complex (Rowley and others, 1995), and the Harmony Hills Tuff likely erupted from the eastern Bull Valley Mountains (Rowley and others, 1995).

Tqh **Harmony Hills Tuff** (lower Miocene) – Resistant, pale-pink to grayish-orange-pink, crystal-rich, moderately welded, dacitic ash-flow tuff; contains about 50% phenocrysts of plagioclase (63%), biotite (16%), hornblende (9%), quartz (7%), pyroxene (5%), and sanidine (trace) (Williams, 1967); yielded an $^{40}Ar/^{39}Ar$ plateau age of 22.03 ± 0.15 Ma (Cornell and others, 2001); as much as 50 feet (15 m) thick.

Exposed in Parowan Canyon where it overlies the Bauers Tuff Member of the Condor Canyon Formation, and reinterpreted by lead-author Biek to structurally underlie the Isom Formation that is part of the Markagunt Megabreccia; also preserved at the base of the Megabreccia in Summit Creek canyon. The source of the Harmony Hills Tuff is unknown, but isopachs are centered on Bull Valley (Williams, 1967), suggesting that it was derived from the eastern Bull Valley Mountains, probably from an early, much more voluminous eruptive phase of the Bull Valley/Hardscrabble Hollow/Big Mountain intrusive arch as suggested by Blank (1959), Williams (1967), and Rowley and others (1995, 2006). Consistent with this interpretation is the fact that its age is nearly identical to that of those intrusions.

Tqcb **Bauers Tuff Member of Condor Canyon Formation** (lower Miocene) – Resistant, light-brownish-gray to pinkish-gray, densely welded, rhyolitic ash-flow tuff; contains about 10 to 20% phenocrysts of plagioclase (40–70%), sanidine (25–50%), biotite (2–10%), Fe-Ti oxides (1–8%), and pyroxene (<3%), but lacks quartz phenocrysts (Rowley and others, 1995); bronze-colored biotite and light-gray flattened lenticules are conspicuous in the upper, vapor-phase part of the tuff; typically about 50 to 100 feet (15–30 m) thick.

Bauers Tuff is exposed in Parowan Canyon where it is as much as 50 feet (15 m) thick and overlies volcaniclastic sandstone and mudflow breccia of the Mount Dutton Formation. It overlies the Leach Canyon Formation in Summit Creek canyon. It is also exposed in a fault block in the Red Hills, where it is as much as about 100 feet (30 m) thick (Maldonado and Williams, 1993a), and in Fivemile Hollow west of Panguitch and on the west flank of the Sevier Plateau at the head of Limekiln Creek where it is about 80 feet (25 m) thick.

The Bauers Tuff erupted from the northwest part (Clover Creek caldera) of the Caliente caldera complex and covered an area of at least 8900 square miles (23,000 km^2) (Best and others, 1989b; Rowley and others, 1995). The prefered $^{40}Ar/^{39}Ar$ age of the Bauers Tuff Member is 22.7 Ma (Best and others, 1989a) or 22.8 Ma (Rowley and others, 1995), which is also the $^{40}Ar/^{39}Ar$ age of its intracaldera intrusion exposed just north of Caliente, Nevada (Rowley and others, 1994b). Fleck and others (1975) reported a K-Ar age (corrected according to Dalrymple, 1979) of 22.7 ± 0.6 Ma (plagioclase) for Bauers Tuff Member on the Markagunt Plateau, east of Fivemile Ridge.

Tql **Leach Canyon Formation** (upper Oligocene) – Grayish-orange-pink to pinkish-gray, unwelded to poorly welded, crystal-rich rhyolite tuff that contains abundant white or light-pink collapsed pumice fragments and several percent lithic clasts, many of which are reddish brown; contains 25 to 35% phenocrysts of plagioclase, slightly less but subequal amounts of quartz and sanidine, and minor biotite, hornblende, Fe-Ti oxides, and a trace pyroxene; forms the resistant caprock of Brian Head peak and the southern part of Black Ledge, is exposed eastward nearly to the Panguitch Lake area, and is also exposed in fault blocks at the west edge of the Markagunt Plateau and in the northern Red Hills, as described below; source is unknown, but it is probably the Caliente caldera complex because isopachs show that it thickens toward the complex (Williams, 1967; Rowley and others, 1995); typically about 100 feet (30 m) thick in the map area.

At Brian Head peak, the Leach Canyon Formation, which unconformably overlies the Isom Formation, consists of four parts, the lower three of which are rarely exposed elsewhere. At the base is nonresistant, 6- to 10-foot-thick (2–3 m), unwelded, white, rhyolite tuff that is overlain by a 10-foot-thick (3 m) moderate-orange-pink rhyolite tuff that has sparse reddish-brown lithic clasts, which becomes slightly more indurated in the upper part of the unit. This is overlain by a massive, 12-foot-thick (4 m) black vitrophyre, which is in turn overlain by a 25-foot-thick (8 m) resistant, pale-red, moderately welded rhyolite tuff that contains pale-lavender flattened pumice lenticules and as much as 1% distinctive, small, reddish-brown lithic clasts of flow rock torn from the vent walls. This resistant upper unit forms the cap rock of Black Ledge northward to beyond the Sidney Peaks area.

To the east, west of Panguitch Lake, the Leach Canyon Formation unconformably overlies the Brian Head Formation or locally stream gravel containing clasts of Isom Formation welded tuff (for example, on the southeast side of Prince Mountain at sample location PL061708-3). Pumice makes up about 10% of the tuff and is typically less than 0.5 inch (1 cm) in length, but somewhat larger near the top of the cooling unit. A nonresistant, moderate-orange-pink ash-fall tuff identical to that at Brian Head peak is present at the base of the unit. The main part of the cooling unit contains only rare, small, reddish-brown lithic fragments.

The Leach Canyon Formation and the Haycock Mountain Tuff are petrographically and chemically similar, which led Sable and Maldonado (1997a) to suggest that the latter is a distal facies of Leach Canyon. While it is true that the two formations are not reliably distinguishable based on their major- and trace-element chemistry, the Haycock Mountain Tuff is typically less welded than the Leach Canyon and contains conspicuous black lithic fragments, unlike the reddish-brown lithic fragments of the Leach Canyon, facts previously noted by Anderson (1993), Rowley and others (1994a), and Hatfield and others (2010). Detailed mapping of the Panguitch Lake and Haycock Mountain quadrangles (Biek and Sable, in preparation; Biek, in preparation) reconfirms that these are indeed two different units. The Leach Canyon Formation can be traced in continuous outcrop from Brian Head peak northward to the head of Bunker Creek and then east to the east end of Prince Mountain just west of Panguitch Lake. It is structurally overlain by the Markagunt Megabreccia, which here consists mostly of the Isom Formation. Samples from the south side of Prince Mountain yielded K-Ar ages of 22.8 ± 1.1 Ma (biotite) and 24.8 ± 1.0 Ma (sanidine) (Rowley and others, 1994a, sample 89USa-1a, which they mistakenly called Haycock Mountain Tuff) and a duplicate K-Ar age of 24.3 ± 1.0 Ma (sanidine) as well as an $^{40}Ar/^{39}Ar$ age of 23.86 ± 0.26 Ma (biotite) (Sable and Maldonado, 1997a, on the same sample 89USa-1a). The Leach Canyon Formation is widely agreed to be about 23.8 Ma (Best and others, 1993; Rowley and others, 1995). As noted by Hatfield and others (2010), both Rowley and others (1994a) and Sable and Maldonado (1997a) misinterpreted this tuff to be the Haycock Mountain Tuff, which yielded a slightly younger $^{40}Ar/^{39}Ar$ age of 22.75 ± 0.12 Ma (sanidine) at its type section one mile (1.6 km) northeast of Panguitch Lake (Sable, unpublished data, 1996; see also Hatfield and others, 2010). The facts that the tuff at Prince Mountain yielded an age analytically indistinguishable from the Leach Canyon Formation, that it can be traced continuously to outcrops at Brian Head peak, and that it is structurally overlain by the Markagunt Megabreccia, are irrefutable evidence that it is the Leach Canyon Formation and not the Haycock Mountain Tuff.

The Leach Canyon Formation unconformably overlies the Isom Formation at Brian Head peak and the southern part of Black Ledge. North of Castle Valley and at Prince Mountain, however, the Leach Canyon unconformably overlies Brian Head strata. This distribution suggests that the Prince Mountain–Castle Valley area was a paleohigh of Brian Head strata during Isom time, and that, once the resistant Isom was in place, this paleohigh was preferentially eroded to form a broad, east-trending stream valley in which the Leach Canyon accumulated; the Leach Canyon is not present on the Markagunt Plateau north of Clear Creek, a west- northwest-trending tributary to Panguitch Lake.

Tbrp **Volcanic rocks of Bull Rush Creek** (upper Oligocene) – Light-brown, light- to dark-gray, pink, and light-greenish-yellow, complexly interbedded, volcanic mudflow breccia, conglomerate, sandstone, lava flows, poorly welded ash-flow tuff with abundant lithic clasts, and autoclastic flow breccias; mineralogically and chemically similar to the Spry intrusion and Buckskin Breccia, and so probably represents a stratovolcano complex on the roof of the intrusion, which is a laccolith (Anderson and Rowley, 1975; Rowley and others, 2005); mapped northeast of Bear Valley Junction where it is interbedded with volcanic mudflow deposits of the Mount Dutton Formation; yielded a K-Ar age of 26.4 ± 3.2 Ma (Anderson and others, 1990a), consistent with that of the Spry intrusion (Rowley and others, 2005); Anderson and others (1990a) reported an incomplete section is about 800 feet (250 m) thick in the adjacent Circleville Canyon area.

Tbb **Buckskin Breccia** (upper Oligocene) – Lithic ash-flow tuff, autoclastic flow breccia(?), and volcanic mudflow breccia comprising at least four undifferentiated, moderately resistant units, locally separated by thin, tuffaceous sandstone, each of which contains clasts of rock petrologically identical to volcanic rocks of Bull Rush Creek and similar to those of the Spry intrusion (Anderson and Rowley, 1975; Anderson and others, 1987, 1990a, 1990b); first noted by Anderson (1965) to contain clasts similar to the Spry intrusion, which increase in size toward the intrusion and which Yannacci (1985) called clasts of juvenile magma (i.e., clasts of identical composition to the matrix, broken up during eruption of pyroclastic flows), all of which suggest that the Buckskin Breccia originated as an eruptive phase of the nearby Spry intrusion; type section is just east of Lower Bear Valley, north of Highway 20 in the extreme northeast corner of the Little Creek Peak quadrangle (Anderson and others, 1987); more than 700 feet (210 m) thick in the Little Creek Peak quadrangle (Anderson and others, 1987), but only a few tens of feet thick west of Bear Valley Junction.

Tis **Spry intrusion** (upper Oligocene) – Light-gray quartz latite porphyry with phenocrysts of plagioclase, hornblende, biotite, and uncommon quartz, sanidine, and pyroxene in a holocrystalline groundmass of quartz, plagioclase, and sanidine; all exposures in this map area exhibit autobrecciation; maximum exposed thickness in the map area is about 300 feet (90 m).

Well exposed along Highway 20 about 1.5 miles (2.5 km) west of Bear Valley Junction, and about 2 miles (3 km) northwest of Bear Valley Junction where it is underlain by Claron Formation and overlain by Mount Dutton Formaton, suggesting that the intrusion there was unroofed prior to deposition of Mount Dutton volcanic mudflows. Previously mapped as Buckskin Breccia and local volcanic rocks by Anderson and Rowley (1987), but reinterpreted here as autoclastic breccias of the Spry intrusion. The bulk of the Spry intrusion, immediately north of the map area, intruded as a laccolith into the Claron Formation (Grant, 1979; Anderson and others, 1987, 1990a), but exposures along Highway 20 are directly overlain by Wah Wah Springs Formation and are thus part of an inferred structurally higher level sill intruded at the top of the Brian Head Formation. Exposed over an area of about 7 square miles (18 km^2) just north of the map area where it straddles the Sevier River at the east edge of the Markagunt Plateau and the west edge of the Sevier Plateau, and in this map area where it underlies several additional square miles west and northwest of Bear Valley Junction. Also inferred to underlie Bear Valley dome immediately west of Bear Valley Junction (Anderson and Rowley, 1987). We report a new U-Pb age on zircon of 26.24 ± 0.62 Ma for the Spry intrusion, which is consistent with a K-Ar age on plagioclase of 26.1 ± 1.8 Ma (Anderson and others, 1990a) on the intrusion and with a K-Ar age on plagioclase of 26.4 ± 3.2 Ma on volcanic rocks at the vent area (Anderson and others, 1990a); (Damon, 1968) reported an anomalously old K-Ar age of 30.4 ± 1.5 Ma.

Tin **Isom Formation and Needles Range Group, undivided** (Oligocene) – Poorly exposed, highly faulted outcrop in the upper reaches of Jackrabbit Wash at the north end of the Red Hills, interpreted by Maldonado and Williams (1993a) as part of the upper plate of their Red Hills shear zone.

Ti **Isom Formation** (upper Oligocene) – Medium-gray, crystal-poor, densely welded, trachydacitic ash-flow tuff, typically having distinctive rheomorphic features including flow folds, elongated vesicles, and flow breccias and thus commonly known as a tufflava (Mackin, 1960; Anderson and Rowley, 2002); small (1–3 mm) euhedral crystals constitute 10 to 15% or less of the rock and are mostly plagioclase (90%) and minor pyroxene and Fe-Ti oxides set in a devitrified-glass groundmass; exhibits pronounced platy outcrop habit and is thus accompanied by extensive talus deposits; rarely, a black basal vitrophyre is exposed, and locally fracture surfaces and elongated vesicles (lenticules, described below) are dark reddish brown to dusky red; query indicates uncertain correlation in the upper reaches of the Clear Creek drainage northwest of Panguitch Lake; the Isom Formation is about 26 to 27 Ma on the basis of many $^{40}Ar/^{39}Ar$ and K-Ar ages (Best and others, 1989b; Rowley and others, 1994a), and because it is locally interbedded with the 26 Ma Buckskin Breccia (Anderson and others, 1987); maximum exposed thickness is about 350 feet (110 m) at Black Ledge and about 250 feet (75 m) along Ipson Creek.

The best and most extensive exposures of the Isom Formation in the map area are at Brian Head peak and to the northeast along Black Ledge where at least three cooling units are locally present. At Brian Head peak, the lower part of the formation is classic tufflava about 80 feet (24 m) thick, whereas the upper part is a flow breccia 60 to 90 feet (18–27 m) thick. Along Black Ledge, about 7 miles (11 km) northeast of Brian Head peak, the flow breccia is absent and the Isom there appears to consist of a single cooling unit about 350 feet (100 m) thick. The Isom also forms prominent cliffs north of Clear Creek and Panguitch Lake.

Regionally, many outcrops of all cooling units in the Isom Formation reveal secondary flow characteristics, including flow breccias, contorted flow layering, and linear vesicles such that the unit was considered a lava flow until Mackin (1960) mapped its widespread distribution (300 cubic miles [1300 km^3] today spread over an area of 9500 square miles [25,000 km^2] Best and others, 1989a) and found evidence of glass shards, thus showing its true ash-flow tuff nature. For that reason it is commonly referred to as a tufflava, and is also called a rheomorphic ignimbrite, an ash-flow tuff that was sufficiently hot to move with laminar flow as a coherent ductile mass—see, for example, Anderson and Rowley (1975, 2002), Andrews and Branney (2005), and Geissman and others (2010). Exhibits pronounced subhorizontal lamination or platiness, which Mackin (1960) called "lenticules." Fryman (1986, 1987), Anderson and others (1990c), and Anderson and Rowley (2002) also described the light-gray, pancake-shaped lenticules, which are typically spaced 4 to 8 inches (10–20 cm) apart and may extend for 30 feet (10 m) or more, and which are locally contorted, suggesting turbulence in the flow as it moved over uneven topography. Fryman (1986, 1987) also described fumaroles in the

Isom of the northern Markagunt Plateau, a result of degassing of the flow as it came to a rest.

The source of the Isom is unknown, but isopach maps and pumice distribution suggest that it was derived from late-stage eruptions of the 27–32 Ma Indian Peak caldera complex that straddles the Utah-Nevada border, possibly in an area now concealed by the western Escalante Desert (Rowley and others, 1979; Best and others, 1989a, 1989b). Estimated crystallization temperature and pressure of phenocrysts of the Isom is 950°C and < 2 kbar (Best and others, 1993), and this relatively high temperature is supported by its degree of welding and secondary flow features. At its type area in the Iron Springs district west of the map area, Mackin (1960) defined three members, a lower unnamed member, the Baldhills Tuff Member, and the upper Hole-in-the-Wall Tuff Member; Rowley and others (1975) redefined the Baldhills Tuff Member to include Mackin's lower unnamed member, and noted that the Baldhills consists of at least six cooling units. Maldonado and Williams (1993a, b) described nine apparent cooling units in the northern Red Hills at the west edge of the map area. In the northern Markagunt Plateau, Anderson and Rowley (1975) defined the Blue Meadows Tuff Member, which underlies the Baldhills Tuff Member, but it is possible that the Blue Meadows Tuff is part of the Mount Dutton Formation, and thus a local tuff of the Marysvale volcanic field (Rowley and others, 1994a). Maldonado and others (2011) mapped the Blue Meadows Tuff Member of the Isom Formation at the east edge of the Cottonwood Mountain quadrangle. For this map, we simply call this ash-flow tuff the Isom Formation, noting our uncertainty in dividing the Isom on the Markagunt Plateau.

Tbt **Three Creeks Tuff Member of the Bullion Canyon Volcanics** (upper Oligocene) – Moderately welded, light-gray, light-brown, and pink, crystal-rich dacitic ash-flow tuff; contains nearly 50% phenocrysts of plagioclase, subordinate hornblende and biotite, and minor quartz, Fe-Ti oxides, and sanidine, and moderately abundant pumice and sparse volcanic rock fragments; lithologically similar to the Wah Wah Springs Formation, but contains more and significantly larger plagioclase (as long as 5 mm) and other phenocrysts; typically autobrecciated in the map area, likely due to late-stage flowage near the distal southern margin of the tuff (Rowley, 1968); yielded K-Ar age of about 27 Ma (Steven and others, 1979); maximum thickness is about 90 feet (30 m) in the map area.

Erupted from the Three Creeks caldera in the southern Pahvant Range (Steven, 1981), forming the largest ash-flow tuff in the Marysvale volcanic field. The estimated volume of the tuff is about 50 cubic miles (200 km^3), but this is a minimum because it is commonly covered near the base of the Bullion Canyon and Mount Dutton volcanic sequences (Cunningham and others, 2007).

Tn **Needles Range Group, undivided** (upper to lower Oligocene) – Lund Formation and Wah Wah Springs Formation undivided in the Red Hills due to map scale.

Tnl **Lund Formation** (upper Oligocene) – Grayish-orange-pink, moderately welded, crystal-rich, dacitic ash-flow tuff exposed in the Red Hills; similar to underlying Wah Wah Springs Formation, but with generally smaller mafic phenocrysts and a lighter-colored matrix; locally contains spheroidal masses of pumice as large as 1 foot (0.3 m) in diameter near the top of the unit; base of the formation includes about 12 feet (4 m) of pale-greenish-yellow tuffaceous sandstone and lesser pebbly volcaniclastic conglomerate; exhibits normal magnetic polarity (Best and Grant, 1987); derived from the White Rock caldera, the southwest part of the older Indian Peak caldera, and is of similar volume to the underlying Wah Wah Springs Formation (Best and Grant, 1987; Best and others, 1989a, b); preferred age is 27.9 Ma (Best and others, 1989a); as much as about 200 feet (60 m) thick (Maldonado and Williams, 1993a).

unconformity

Tnw **Wah Wah Springs Formation** (lower Oligocene) – Pale-red to grayish-orange-pink, moderately welded, crystal-rich, dacitic ash-flow tuff that rests on Brian Head strata and, on the Markagunt Plateau, is overlain by the Isom Formation; phenocrysts of plagioclase, hornblende, and biotite, (plus minor quartz, Fe-Ti oxides and sanidine) constitute about 40% of the rock; the abundance of hornblende over biotite is unique among Great Basin ignimbrites; elongate collapsed pumice is common; exposed west of Cottonwood Mountain and west of Bear Valley in the northern Markagunt Plateau, at the head of Bunker Creek west of Panguitch Lake, and in the Red Hills; exhibits reversed magnetic polarity (Best and Grant, 1987); derived from the Indian Peak caldera of the 27 to 32 Ma Indian Peak caldera complex that straddles the Utah-Nevada border (Best and others, 1989a, 1989b); today, the Wah Wah Springs covers at least 8500 square miles (22,000 km^2) with an estimated volume as much as about 720 cubic miles (3000 km^3) (Best and others, 1989a); about 30 Ma based on many K-Ar and ^{40}Ar/^{39}Ar age determinations (Best and Grant, 1987; Best and others, 1989a, b; Rowley and others, 1994a); about 40 feet (12 m) thick near the west edge of the Markagunt Plateau, but as much as 400 feet (120 m) thick in the Red Hills (Maldonado and Williams, 1993a, b).

A small exposure on Lowder Creek (east of Brian Head peak) is deeply weathered, nonresistant, white, crystal-rich ash-flow tuff about 6 feet (2 m) thick. Phenocrysts of plagioclase, hornblende, biotite, and quartz (plus minor Fe-Ti oxides and sanidine) make up about 30 to 40% of the rock. The color and degree of welding contrast sharply with typical Wah Wah Springs, which led Rowley and others (in preparation) to suggest that the tuff at Lowder Creek was deposited in a lake. Biotite-hornblende pairs from two samples from the same bed at Lowder Creek yielded K-Ar ages of 29.1 to 32.4 Ma (Rowley and others, 1994). The Lowder Creek exposure is overlain by 3 to 6 feet (1–2 m) of volcanic mudflow breccia, which is in turn overlain by 10 to 15 feet (3–5 m) of deeply weathered, nonresistant, crystal-poor ash-flow tuff(?) of uncertain provenance, which is itself overlain by autochthonous Isom Formation.

unconformity

Brian Head Formation (lower Oligocene to middle Eocene) – The Brian Head Formation is the oldest widespread Tertiary volcaniclastic unit in the region. On the Markagunt Plateau, it disconformably overlies the uppermost mudstone, siltstone, and sandstone interval (Tcwt) of the white member of the Claron Formation (in the northwestern Markagunt Plateau, where the white member appears to be missing, Brian Head strata overlie the pink member of the Claron Formation). On the Sevier Plateau, Brian Head strata, which locally include a basal variegated unit not present to the west, disconformably overlie the conglomerate at Boat Mesa. Sable and Maldonado (1997b) designated a type section at Brian Head peak and divided the Brian Head Formation into three informal units, ascending: (1) nontuffaceous sandstone and conglomerate, (2) a volcaniclastic unit that has minor but conspicuous limestone and chalcedony, and (3) a volcanic unit, locally present in the northern Markagunt Plateau but not at the type section, characterized by volcanic mudflow breccia, mafic lava flows, volcaniclastic sandstone and conglomerate, and ash-flow tuff. We include the basal nontuffaceous sandstone and conglomerate as a new uppermost part of the Claron Formation (Tcwt), thus further restricting the Brian Head Formation to a widespread volcaniclastic unit (Tbh) and a local volcanic unit (Tbhu) present only in the northern Markagunt Plateau. On the Sevier Plateau, we divide the Brian Head Formation into four informal units (in ascending order, Tbhv, Thb_1, Tbh_2, and Tbh_3).

On the Markagunt Plateau, Brian Head strata are unconformably overlain by the 30 Ma Wah Wah Springs Formation (Tnw), or locally by the 26 to 27 Ma Isom Formation (Ti) or the 24 Ma Leach Canyon Formation, whereas on the Sevier Plateau, Brian Head strata are typically overlain by the Mount Dutton Formation. Fleck and others (1975) reported a K-Ar age of 31.0 ± 0.5 Ma on a local, crystal-poor ash-flow tuff at the base of the volcanic section from just north of Showalter Mountain, immediately north of the map area in the Burnt Peak 7.5' quadrangle (Anderson and Rowley, 1975, p. 12–13). Maldonado and Moore (1995) reported $^{40}Ar/^{39}Ar$ ages of 33.00 ± 0.13 Ma (plagioclase) and 33.70 ± 0.14 Ma (biotite) on an ash-flow tuff in the northern Red Hills that lies in the upper part of the formation. Davis and others (2009) reported U-Pb (SHRIMP-RG) ages of 35.2 ± 0.8 Ma and 34.7 ± 0.6 Ma from the Brian Head Formation at Brian Head peak. We obtained U-Pb ages on zircon from airfall tuffs at the base of the formation at Cedar Breaks National Monument of 35.77 ± 0.28 Ma, from about 80 feet (25 m) above the base of the formation on the southwest flank of the Sevier Plateau of 36.51 ± 1.69 Ma, and from near the top of the formation near Haycock Mountain of 34.95 ± 0.83 Ma and 33.55 ± 0.80 Ma; the two Haycock Mountain samples also yielded $^{40}Ar/^{39}Ar$ ages on sanidine of 35.04 ± 0.23 Ma and 33.80 ± 0.05 Ma (UGS and NIGL, 2012). Eaton and others (1999c) and Korth and Eaton (2004) reported on Duchesnean (middle Eocene) vertebrate fossils in the variegated unit, here assigned to the basal Brian Head Formation. The Brian Head Formation is thus early Oligocene to latest middle Eocene. Golder and Wizevich (2009) and Golder and others (2009) described trace fossils, including possible crayfish burrows and root traces, in the Brian Head Formation on the Sevier Plateau.

Tbhu **Upper volcanic unit** – Volcanic mudflow breccia, lava flows, and lesser ash-flow tuff west-southwest of Bear Valley Junction, where it was called local volcanic and sedimentary strata by Anderson and Rowley (1987); also mapped northwest of Adams Head on the southwest Sevier Plateau; about 700 feet (200 m) thick.

Tbht **Rhyolitic tuff of middle volcaniclastic unit** – Pinkish-brown, unwelded rhyolite ash-flow tuff in the upper part of the formation in the northern Red Hills, on the west flank of Jackrabbit Mountain; yielded K-Ar ages of 34.2 ± 2.1 Ma (plagioclase) and 36.3 ± 1.3 Ma (biotite), and $^{40}Ar/^{39}Ar$ ages of 33.00 ± 0.13 Ma (plagioclase) and 33.70 ± 0.14 Ma (biotite) (Maldonado, 1995); as much as about 200 feet (60 m) thick.

Tbh **Middle volcaniclastic unit, undivided** – White to light-gray volcaniclastic mudstone, siltstone, silty sandstone, sandstone, conglomerate, volcanic ash, micritic limestone, and multi-hued chalcedony; near Mineral Canyon and northwest of Little Salt Lake (hill 7292), conglomerate consists of pebble- to boulder-size, rounded clasts of intermediate volcanic rocks of unknown affinity and quartzite pebbles and cobbles; sandstone is commonly bioturbated with pencil-size root or burrow casts that weather out in relief; soft-sediment slump features are locally common; chalcedony is various shades of white, gray, yellow, red, black, and brown, typically has a white weathering rind, is commonly highly brecciated and resilicified, typically occurs in beds 1 to 3 feet (0.3–1 m) thick but locally as much as 8 feet (2.5 m) thick, is locally stained by manganese oxides, and may have resulted from silicification of limestone beds (Maldonado, 1995; Sable and Maldonado, 1997b) or possibly volcanic ash beds (Bakewell, 2001); chalcedony is almost always highly fractured, but some is useful for lapidary purposes (Strong, 1984); about 500 feet (150 m) thick at Brian Head peak; on the southwest flank of the Sevier Plateau, Brian Head strata are readily divisible into four informal parts that collectively total about 1000 feet (300 m) thick, described below.

The formation is typically nonresistant, poorly exposed, and extensively covered by colluvium, but locally well exposed near Panguitch Lake and on the southwest side of Brian Head peak. Because of abundant bentonitic clay derived from weathered volcanic ash, this unit weathers to strongly swelling soils (unlike the underlying Claron Formation) and forms large landslide complexes; it was also the principal detachment surface for the Markagunt Megabreccia. The Brian Head Formation was deposited in low-relief fluvial, floodplain, and lacustrine environments in which large amounts of volcanic ash accumulated (Sable and Maldonado, 1997b).

Tbh_3 **Upper part of middle volcaniclastic unit** – Similar to the middle volcaniclastic unit described above, but contains more sandstone and lesser mudstone and few beds of chalcedony; contains several tens of feet of apparently non-volcaniclastic Claron-like redbeds near the middle of the unit on the southeast flank of the Sevier Plateau; about 700 feet (210 m) thick.

Tbh_2 **Middle part of middle volcaniclastic unit** – Volcaniclastic fine-grained sandstone, siltstone, and mudstone; forms distinctive, green, red, and gray band in lower part of the formation on the Paunsaugunt Plateau; about 80 feet (25 m) thick.

Tbh_1 **Lower part of middle volcaniclastic unit** – Light-gray and white volcaniclastic mudstone, siltstone, and fine-grained sandstone; basal part includes a 25-foot-thick (8 m) airfall tuff that weathers to bluish-gray swelling soils and which yielded a U-Pb age on zircon of 36.51 ± 1.69 Ma; about 160 feet (50 m) thick.

Tbhv **Variegated part of middle volcaniclastic unit** – Very fine to fine-grained, slope-forming sandstone, siltstone, and mudstone of red, pink, yellowish-brown, and purplish-gray hues; non-volcaniclastic, but some mudstone intervals exhibit swelling soils that suggest a volcanic ash component; overlies the conglomerate at Boat Mesa; present only at the south end of the Sevier Plateau, in Casto Canyon and areas to the south where it is 0 to about 160 feet (50 m) thick; Sable and Maldonado (1997b) reported that the unit is 50 to 125 (16–38 m) thick in the Casto Canyon area.

Bowers (1972) first noted similarity to the Colton Formation of central Utah. Eaton and others (1999c) and Korth and Eaton (2004) reported on vertebrate fossils from this "variegated" interval on the southwest Sevier Plateau—a fauna dominated by aquatic taxa suggestive of lacustrine paleoenvironments—which they assigned to the Duchesnean North American Land Mammal Age (end of middle Eocene). Feist and others (1997) also reported on sparse late middle Eocene vertebrate fossils and charophytes from these beds.

unconformity

Tbm, Tbml

Conglomerate at Boat Mesa (middle Eocene) – Contains three distinct, non-volcaniclastic intervals, the lower two of which are mapped separately as Tbml. Uppermost ledge-forming interval (Tbm) is mostly light-gray conglomerate, lesser light-gray to light-brown calcareous sandstone and conglomeratic sandstone, and minor white to light-gray limestone and conglomeratic limestone; clasts are rounded pebbles of black chert, brown, gray, and distinctive greenish quartzite, and lesser Paleozoic limestone; no volcanic or intrusive clasts are present; in the limestone intervals, clasts commonly appear to float in a carbonate mud matrix, but otherwise the conglomerates are clast supported. The lower two intervals (Tbml) include an upper part of slope-forming, reddish-brown and light-gray, thin- to medium-bedded, fine- to medium-grained sandstone, siltstone, and mudstone a few feet to about 30 feet (9 m) thick, and a lower, ledge-forming interval that is yellowish- to reddish-brown, very thick bedded pebbly conglomerate containing clasts similar to the upper interval but lacking green quartzite pebbles; this combined interval pinches out at the south end of the Sevier Plateau, south of the South Fork Limekiln Creek, but reappears farther south in Bryce Canyon National Park (it is lumped with Tbm between Bryce Point and Inspiration Point due to map scale); about 100 feet (30 m) thick at Boat Mesa in Bryce Canyon National Park (Bowers, 1990) and typically about 50 to 100 feet (15–30 m) thick on the southwest flank of the Sevier Plateau; on the Markagunt Plateau, a thin pebble conglomerate that unconformably overlies the Claron Formation, and that we suggest is a westward facies of the conglomerate at Boat Mesa, is a few feet to perhaps 10 feet (3 m) thick and is so mapped as a marker bed.

The conglomerate at Boat Mesa unconformably overlies the white member of the Claron Formation. It is especially well developed at its namesake Boat Mesa in Bryce

Canyon National Park, and on the southwest flank of the Sevier Plateau where it unconformably overlies—and ultimately cuts out—the upper limestone interval of the white member (Tcwu) of the Claron Formation and is in turn overlain by the lower unit (Tbh_1) of the Brian Head Formation or by the variegated part of the middle volcaniclastic unit (Tbhv). The upper part of the conglomerate at Boat Mesa (Tbm) weathers to a white ledge, making it difficult to distinguish from the upper white limestone unit of the Claron Formation on aerial photos or from a distance.

The conglomerate at Boat Mesa represents deposits of braided stream channels and minor floodplains incised into deposits of the Claron Formation. It was suggested by Bowers (1990) to be Oligocene and by Davis and Pollock (2010) to be Oligocene or Miocene, but lack of volcanic clasts suggests latest middle Eocene age, confirmed by an overlying 36.51 ± 1.69 Ma volcanic ash in the Brian Head Formation (unit Tbh_1). We also obtained a U-Pb detrital age on zircon of $37.97 +1.78 - 2.70$ Ma (Gary Hunt, UGS, written communication, March 7, 2012) for Tbm on the southwest flank of the Sevier Plateau. This sample also yielded a Middle Jurassic peak of about 168 Ma from a coherent group of 34 grains, indicating that Middle Jurassic volcanic or intrusive rocks provided a significant source of sediment to the formation even though it lacks such clasts.

unconformity

Claron Formation (Eocene to Paleocene) – Claron Formation strata are among the most visually arresting rocks in southwestern Utah, but because the formation lacks a type section and was named for incomplete, fault-bounded exposures in the Iron Springs mining district, the nomenclatural history of these rocks is complicated. Mackin (1947) first applied the name Claron Formation to strata of the Markagunt Plateau, noting the similarity with rocks in the Iron Springs mining district to which Leith and Harder (1908) first applied the name. Bowers (1972) subdivided the Claron Formation into three informal members on the Table Cliff Plateau immediately east of the map area: ascending, the lower pink, white limestone, and variegated sandstone members. We suspect that Bowers' variegated member is a thicker equivalent to what we map as the conglomerate at Boat Mesa (Tbm and Tbml) and overlying non-volcaniclastic Brian Head strata (Tbhv) on the south flank of the Sevier Plateau. Anderson and Rowley (1975) provide the best review of this nomenclatural history, although since then, additional mapping and stratigraphic work has enabled the upper part of their Claron Formation to be split off as the conglomerate at Boat Mesa and the Brian Head Formation as described above. Anderson and Rowley (1975) considered the formation to have two informal members, a lower red member and an upper white member, but, based on precedence and a long informal usage of the term "pink" when referring to the uppermost part of the Grand Staircase and its strata, we retain Bowers' term pink member for the lower Claron. We further subdivide the white member and restrict it to nonvolcaniclastic strata unconformably overlain by the conglomerate at Boat Mesa, and note that the pink member has long been known informally as the red member on the Markagunt Plateau.

We thus map the Claron Formation as two members made up of five informal lithostratigraphic units described below: the upper white member (which is divided into an uppermost mudstone unit, an upper limestone unit, a middle mudstone and sandstone unit, and a lower limestone unit) and the lower pink member. The several lithologic facies of the white member of the Claron are here mapped separately for the first time, which has proven useful to better understand faulting at the west edge of the Markagunt Plateau, the distribution of overlying volcaniclastic strata of the Brian Head and Limerock Canyon Formations, and the southern depositional limit of the Markagunt Megabreccia and location of inferred toe thrusts.

The Claron Formation consists of mudstone, siltstone, sandstone, limestone, and minor conglomerate deposited in fluvial, floodplain, and lacustrine environments of an intermontaine basin bounded by Laramide uplifts; the pink member is almost wholly fluviatile and the white member is both lacustrine and fluviatile (Goldstrand, 1990, 1991, 1992, 1994; Bown and others, 1997). Ott (1999) recognized a 130-foot-thick (40 m) interval of mostly medium-bedded bioclastic limestone and thin-bedded micritic limestone with gastropods, ostracods, charophytes, and algal filaments in the lower part of the pink member in Bryce Canyon National Park; this lacustrine interval does not appear to be present in western exposures, suggesting that lacustrine strata are better developed in the central part of the basin. Much of the pink member, and clastic parts of the white member, were greatly modified by bioturbation and pedogenic processes, creating a stacked series of paleosols (Mullett and others, 1988a, b; Mullett, 1989; Mullett and Wells, 1990; see also Bown and others, 1997). Ott (1999) identified cyclicity within the Claron Formation at Bryce Canyon National Park, with several-meter-scale regressive cycles with increasing pedogenesis toward their tops stacked one upon the other. Bown and others (1997) reported on trace fossils of ants, wasps, and bees in the upper part of the pink member and lower part of the white member, recording nest activity during paleosol formation. Hasiotis and Bown (1997) reported on crayfish burrows in Claron strata of the Markagunt Plateau that record relatively deep and highly fluctuating water tables in the pink member, and relatively shallow water tables in alluvial parts of the white member. Davis and others (2008) used isotopic and elemental records preserved in authigenic calcite from samples in the Claron, Flagstaff, and Uinta lake basins to better understand Paleogene landscape evolution of Utah, showing an along-strike migration of a high-elevation landscape from north to south over time and, in southwest Utah, a transition from a closed to open basin beginning with deposition of the white member; Ott (1999) also showed that the pink member was deposited in a hydrologically closed basin. Detrital zircon studies of the Claron Formation from the Escalante Mountains east of the map area show that the formation there was largely derived from erosion of lower Paleozoic sandstones exposed in surrounding Laramide uplifts (Link and others, 2007; Larsen and others, 2010). The Claron Formation is typically forested and covered by colluvium, but it forms the Pink Cliffs, the uppermost riser of the Grand Staircase, and is spectacularly exposed at Cedar Breaks National Monument and Bryce Canyon National Park.

The Claron Formation is unconformably overlain by the conglomerate at Boat Mesa, or, where the conglomerate is apparently locally absent on the west flank of the Markagunt Plateau, by the Brian Head Formation. It appears that the white member of the Claron Formation is locally missing on the west flank of the Markagunt Plateau, for example, southeast of Parowan and northeast of Paragonah, and the conglomerate at Boat Mesa is thin or missing there as well. We are uncertain if this represents nondeposition or erosion of white member strata, but suspect the former, implying that this area was the former northwestern margin of lacustrine deposition. It is possible that clastic strata of the uppermost pink member in western exposures are coeval basin-margin facies of lacustrine strata of the white member in eastern exposures.

On the Paunsaugunt Plateau, south-vergent thrust faults place Upper Cretaceous strata on the pink member of the Claron Formation. The faults were rediscovered in the mid-1980s, when University of Arizona geologists George Davis and Robert Krantz noticed small-displacement thrust faults at Bryce Canyon National Park; their "discovery" fault is none other than the small south-dipping thrust at Bryce Point (Davis and Krantz, 1986). Though small, this fault is so prominent that it is hard to believe it could go undetected for so long, especially considering the scores of geologists who have cast their eyes over that landscape (Davis, 1990, 1991). But Davis was primed for the discovery, as just the day before he examined a low-angle fault zone where State Highway 12 cuts through the Claron Formation at the north end of the park, brought to his attention by U.S. Geological Survey geologist Richard Hereford, and reasoned that that fault may exhibit thrust movement. Davis (1997a,b) provides an engaging account of the rediscovery of what is now known as the Rubys Inn thrust fault zone, originally interpreted by Gregory (1951) as a west-trending horst bounded by high-angle normal faults. Davis's student Eric Lundin first mapped the fault zone in detail, outlining many of its salient features (Lundin, 1987, 1989; Lundin and Davis, 1987). Davis (1987b, p. 72) relates that "During the course of Lundin's mapping, I took him to the site where Bob Krantz and I had reinterpreted the Rubys Inn fault as a thrust. There, in an out-of-the-way place on the poor outcrop I was amazed to find a Chevron business card neatly tucked underneath a fist-sized rock placed on the trace of the Ruby's Inn thrust, at a location approximately midway between the Paunsaugunt and Sevier faults. It was Frank Royse's business card. He had left it there, and had written on the back side of the card, "Hi George! How 'bout this crazy fault?" Though their work was unpublished, Chevron geologists discovered this thrust fault in the mid-1950s!

Because the Rubys Inn thrust fault zone is at right angles to the expected orientation of Sevier and Laramide structures in the region, and because it involves strata that were thought to post-date those orogenies, the cause of the thrust faulting remained poorly understood until 1993. Lundin (1987, 1989) showed that the thrust faults form an arcuate belt around the southeast margin of the Marysvale volcanic field and that they sole into Middle Jurassic evaporates, but was uncertain of their tectonic significance. Nickelsen and Merle (1991) and Nickelsen and others (1992) showed that southward-directed compressional deformation extended as much as 12 miles (20 km) south of the thrust fault zone on both the Paunsaugunt and Markagunt Plateaus. May and others (2011) and Leavitt and others (2011) also documented compressional deformation as much as 18 miles (29 km) south of the thrust on the Paunsaugunt Plateau, and noted similar structures in Cedar Canyon. Nickelsen and others (1992) and Davis and Rowley (1993) first suggested that deformation may be due to laccolith emplacement in the southern part of the Marysvale volcanic field, an idea expanded upon by Merle and others (1993a,b), who suggested that the thrust fault zone formed about 20 to 30 million years ago in response to gravitational collapse of, and/or emplacement of batholithic intrusions into, the Marysvale volcanic field. Interestingly, Merle and others (1993a) failed to find evidence of compressional deformation in the conglomerate at Boat Mesa, which they thus thought post-dated thrust deformation but which we now know to be about 38 Ma.

Based on exposures northwest of Johns Valley, in the northwest part of the Flake Mountain East quadrangle, the conglomerate at Boat Mesa is clearly folded concordantly with underlying Claron strata in the upper plate of the Johns Valley thrust fault, as is overlying Brian Head Formation, and, we suspect, Mount Dutton Formation.

Based on earlier work and our new mapping, the age of thrusting on the Paunsaugunt Plateau can only be definitively constrained as postdating the 37 to 31 Ma Brian Head Formation and predating basin-fill deposits (Taf, Tvg) of poorly constrained Miocene age. Why the conglomerate at Boat Mesa fails to show evidence of widespread, small-scale compressional deformation, as is so well developed in the underling Claron Formation, we do not know. Still, following the "two-tiered" model of Davis (1997a,b, 1999), we envision the thrusts as directed outward from the Marysvale volcanic field, which spread and collapsed under its own weight, resulting in southward-directed thrust faults rooted in evaporite strata of the Middle Jurassic Carmel Formation.

On the Markagunt Plateau, we find no evidence of large-scale older-on-younger relationships indicative of thrust faulting. However, along trend with the Rubys Inn thrust fault, tilted Claron strata near Panguitch Lake, and tilted Isom Formation at Haycock Mountain, suggest having been folded above a blind thrust that, at Haycock Mountain, ramped up and soled into the Brian Head Formation; a deeper thrust would be required to fold Claron strata near Panguitch Lake. On the south side of Haycock Mountain, the upper few tens of feet of Brian Head strata are typically deformed by shears and recumbant folds, but it is unclear if this deformation is due to related thrust faults or emplacement of the Markagunt Megabreccia. The 20 to 21 Ma Limerock Canyon Formation, present only at Hatch Mountain and Mammoth Ridge, may be preserved in a subtle basin south of this inferred blind thrust, implying that thrust faulting took place near the end of major calc-alkaline volcanic activity in the southern part of the Maysvale volcanic field. Alternatively, the folding may reflect the location of these strata on the southeast limb of a poorly expressed syncline that clearly folds the 5 Ma Fivemile Ridge lava flow northeast of Panguitch Lake, a fold possibly related to an inferred segment boundary on the Sevier fault zone.

The age of the white member is well constrained as late middle Eocene (Duchesnean Land Mammal Age) based on sparse vertebrate fossils from this unit on the eastern Markagunt Plateau (Eaton and others, 2011); by limiting ages of 35.77 ± 0.28 Ma and 36.51 ± 1.69 Ma for overlying basal Brian Head Formation on the Markagunt and Sevier Plateaus, respectively; and by a U-Pb detrital zircon age of 37.97 +1.78 – 2.70 Ma from the conglomerate at Boat Mesa on the southwestern Sevier Plateau. Middle Eocene vertebrate fossils and charophytes are also known in basal Brian Head strata on the southwestern Sevier Plateau (Eaton and others, 1999c; Feist and others, 1997).

The maximum age of the pink member, however, is poorly constrained. Goldstrand (1990) reported unspecified late Paleocene palynomorphs from lower Claron strata on the east side of the Pine Valley Mountains, and noted the Paleocene to Eocene gastropods *Viviparus trochiformis*, *Physa* sp., and *Goniobasis* sp. from the pink member (Table 2). Goldstrand (1992, 1994) suggested that the pink member may be time transgressive, being older in western exposures and possibly no older than middle Eocene on the Table Cliff Plateau. This idea, however, was based on fission-track analysis of a single sample from the underlying Pine Hollow Formation, which we consider suspect. For one, such a young age seems at odds with the time required to accummulate such a thick stack of mature paleosols. The inferred young age also appears at odds with the apparently gradational contact between uppermost Wahweap and Grand Castle (redefined) and Claron strata on the Markagunt Plateau, discussed below. Larsen and others (2010) suggested a late Paleocene to early Eocene age for the underlying Pine Hollow Formation on the Table Cliff Plateau, although they noted a complete lack of fossils, datable ash layers, or age-constraining detrital zircons on which to constrain that assumption. Bowers (1972) also noted a complete lack of datable materials in the Pine Hollow, and although he preferred a Paleocene(?) age for the formation, he correctly noted that a latest Cretaceous age cannot be ruled out, as did Anderson and Rowley (1975) and Rowley and others (1979). Given our current understanding of the lower Claron Formation and its paucity of datable materials, we consider it possible that basal pink member strata are latest Cretaceous in age. Anderson and Dinter (2010) showed that lower Claron strata are cut by and gently folded above a large, east-vergent, Sevier-age thrust fault near Parowan Gap, showing that the last stages of thrust faulting in southwest Utah continued into lower Claron time; our new mapping further shows that minor extensional relaxation occurred on this thrust fault. Previously, Claron and underlying Grand Castle strata were thought to postdate Sevier thrust faulting in southwest Utah.

Table 2. Goldstrand (1991) Claron samples.

Sample Number	UTM Northing	UTM Easting	7.5' Quadrangle	Formation	Identification
23-88	4162620	397890	Bryce Point	Claron	*Physa* sp.?
31-88	4177720	425000	Upper Valley	Claron	*Viviparus trochiformis*
3 89	4137550	296410	Pintura	Claron	palynomorph
1 90	4137910	295110	Pintura	Claron	*Goniobasis* sp.?

Note: Sample 3 89 easting given incorrectly as 496410.

Tcw **White member, undivided** (Eocene) – Lithologies are described below for individual units. On the Markagunt Plateau, used for areas south of Blue Spring Mountain (southwest of Panguitch Lake) and west of Brian Head peak where incomplete and isolated exposures preclude subdivision; also used on the southeastern Sevier Plateau where intervening clastic intervals lose character and most of the member appears to be white micritic limestone, and at Flake Mountain, where what we map as the white member may in fact be the pink member.

We also map the white member at Boat Mesa and northward along the escarpment in the northeast part of Bryce Canyon National Park; Bowers (1990), however, mapped these strata as the pink member. Ledge-forming white limestone typical of the white member is present on hill 8155 west of Boat Mesa, but appears to grade east and north into interbedded varicolored mudstone, siltstone, and limestone that weathers to distinctly lighter colored slopes than the underlying pink member.

In aggregate, the white member maintains a relatively uniform thickness of about 350 to 450 feet (105-135 m) on the Markagunt and Paunsaugunt Plateaus. However, the member thickens to the east where it is dominated by white micritic limestone and is about 550 feet (170 m) thick on the Table Cliff Plateau (Bowers, 1973). The entire white member is about 340 feet (100 m) thick in Rock Canyon southeast of Panguitch Lake. Hatfield and others (2010) reported that it is 360 feet (110 m) thick at Cedar Breaks National Monument, but if the lower sandstone and conglomerate unit of Sable and Maldonado (1997b) is included as part of the white member, as suggested here, the thickness is 440 feet (135 m) (regardless, the white member is truncated south of Cedar Breaks National Monument by late Tertiary and Quaternary erosion associated with development of the Markagunt Plateau). Moore and others (1994) reported significant facies changes in the white member near Asay Bench, but there, in aggregate, it is 448 feet (137 m) thick. The white member is about 350 feet (105 m) thick on the southern Sevier Plateau. Ott (1999) measured an incomplete section of 233 feet (71 m) of the white member near Bryce Point, but it is unclear if her lower contact is the same as that used in this map.

Tcwt **Uppermost mudstone, siltstone, and sandstone unit of white member** (upper and middle Eocene) – Varicolored and commonly mottled, pale-reddish-orange, reddish-brown, moderate-orange-pink, dark-yellowish-orange, and grayish-pink calcareous mudstone and siltstone, locally with minor fine-grained silty sandstone and micritic limestone; indistinguishable in lithology and color from the middle white (Tcwm) and pink members (Tcp) of the Claron Formation

Forms a brightly colored slope on top of the upper white member of the Claron Formation in the northern part of Cedar Breaks National Monument (figure 4), where it is best exposed near the North View overlook. There, it is 109 feet (33 m) (Schneider, 1967) of mudstone and siltstone capped by a thin calcareous sandstone and pebbly conglomerate, described below. Also exposed immediately south of Panguitch Lake, where it is about 50 feet (15 m) thick, and in the upper reaches of Rock Canyon. This unit is queried near Winn Gap at the south end of the Red Hills, where, based on similar four-part limestone-clastic-limestone-clastic section above the pink member, we infer that the white member may be present. The unit is thin or absent on the southeastern Markagunt Plateau and on the Sevier Plateau.

Schneider (1967) reported biotite in some of these beds, and while some beds exhibit slightly expansive soils, we found no biotite—even so, it was the apparent presence of biotite-bearing strata, and possible correlation to variegated strata on the southern Sevier Plateau (see Feist and others, 1997), that led Sable and Maldonado (1997b) to provisionally include these strata as a basal part of their Brian Head Formation. However, in light of the absence of tuffaceous material in these beds, these same exposures strongly suggest to us that the nontuffaceous sandstone and conglomerate as defined by Sable and Maldonado (1997b) is more simply an uppermost unit of the Claron Formation (Tcwt) and the overlying conglomerate at Boat Mesa (Tbm, Tbml). We place an unconformity at the base of the thin sandstone and conglomerate (not at the top of the limestone ledge of the white member), thereby including the Claron-like red beds as a new upper unit of the white member. Similar strata are present above the conglomerate at Boat Mesa on the southwest flank of the Sevier Plateau, but because they lie above, not below, the conglomerate, we assign them to the basal unit (variegated unit, Tbhv) of the Brian Head Formation.

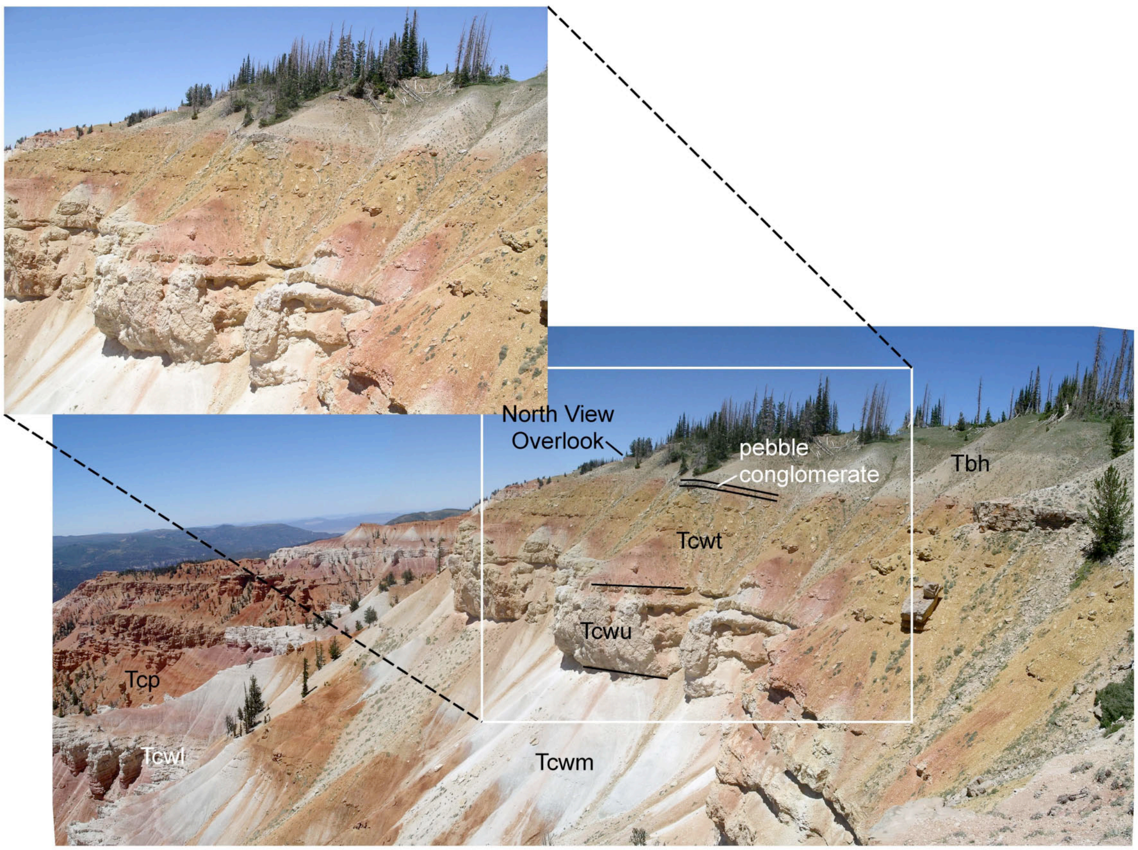

Figure 4. View northwest to North View Overlook at Cedar Breaks National Monument showing contact between Claron and Brian Head strata (the North View Overlook is on basal strata of the gray volcaniclastic unit of the Brian Head Formation, Tbh). Sable and Maldonado (1997b) assigned variegated, nontuffaceous mudstone, siltstone, and minor sandstone and pebble conglomerate (here labeled Tcwt, 109 feet [33 m] thick) to their lower Brian Head Formation. However, these strata appear identical to strata of the middle white unit (Tcwm); they are nontuffaceous and appear simply to be an uppermost facies of the white member of the Claron Formation, to which we assign them. The top of the Claron, as defined here, is marked by a thin, calcareous, pebbly sandstone that has rounded clasts of chert, quartzite, and Claron limestone but no volcanic clasts. Tcp = pink member, Tcwl = lower limestone unit of the white member, of the Claron Formation.

Tcwu **Upper limestone unit of white member** (Eocene) – White, pale-yellowish-gray, pinkish-gray, and very pale orange micritic limestone and uncommon pelmicritic limestone, locally containing intraformational rip-up clasts; locally contains sparse charophytes and planispiraled snails; typically poorly bedded and knobby weathering; locally vuggy with calcite spar and commonly cut by calcite veinlets; resistant and so forms prominent ledge and flat ridge tops; upper conformable contact with Tcwt corresponds to a pronounced color change from white to very pale orange micritic limestone below to brightly colored reddish-orange mudstone and siltstone above; queried at the south end of the Red Hills, and near Mineral Canyon northeast of Paragonah.

The upper limestone unit of the white member thickens irregularly to the east and varies from about 30 to 180 feet (10–55 m) thick, but some of this variation may be due to difficulties in placing the locally gradational contacts. The unit is 45 to 60 feet (14–18 m) thick at Cedar Breaks (Schneider, 1967; Moore and others, 2004; Rowley and others, in preparation) and about 30 feet (10 m) thick in the southern Red Hills (Threet, 1952). It is about 80 to 100 feet (24–30 m) thick in the Black Rock Valley area south-southeast of Panguitch Lake, 80 to 165 feet (24–50 m) thick southwest of Hatch in the Asay Bench quadrangle (Moore and others, 1994), and about 150 to 180 feet (45–55 m) thick near Houston Mountain north-northeast of Navajo Lake (Biek and others, 2011). It is typically about 80 to 100 feet (25–30 m) thick on the southern flank of the Sevier Plateau, but north of the latitude of Limekiln Creek, it grades into a mudstone-dominated interval similar to that of the underlying middle unit.

Tcwml **Lower limestone unit and middle mudstone, siltstone, and sandstone unit of white member, undivided** (Eocene) – Locally undivided at Cedar Breaks National Monument due to map scale, and about 5 miles (8 km) to the east at Houston Mountain due to poor exposure. As mapped, less than about 250 feet (75 m) thick.

Tcwm **Middle mudstone, siltstone, and sandstone unit of white member** (late middle Eocene) – Varicolored and commonly mottled, pale-reddish-orange, reddish-brown, moderate-orange-pink, yellowish-gray, dark-yellowish-orange, and grayish-pink calcareous mudstone and siltstone, and minor fine-grained calcareous sandstone and chert-pebble conglomerate that weathers to a poorly exposed slope; upper conformable contact corresponds to a pronounced color change from brightly colored reddish-orange mudstone and siltstone below to white to very pale orange micritic limestone above; queried at the south end of the Red Hills, and near Willow Creek northeast of Paragonah.

As mapped on the southwest side of the Sevier Plateau, consists of a deep reddish-orange siltstone and mudstone interval about 60 feet (18 m) thick that becomes difficult to identify north of Limekiln Creek. About 120 feet (36 m) thick near Cameron Troughs south of Panguitch Lake, but appears to thin abruptly to about 50 feet (15 m) thick about one mile (1.6 km) to the north. At Cedar Breaks National Monument, Schneider (1967) measured 227 feet (69 m) of strata we assign to Tcwm, but Rowley and others (in preparation) reported that this interval is 310 feet (94 m) thick in this same area. Moore and others (1994) reported that their middle sandy unit is 175 to at least 220 feet (54–67 m) thick in the Asay Bench quadrangle southwest of Hatch.

Eaton and others (2011) reported the first sparse late middle Eocene (Duchesnean Land Mammal Age) vertebrate fossils and ostracods of *Cypris* sp. from this unit on the eastern Markagunt Plateau.

Tcwl **Lower limestone unit of white member** (Eocene) – Micritic limestone similar to the upper white limestone interval (Tcwu); forms cliff or steep, ledgy, white slope above more colorful but typically subdued slopes of the pink member (Tcp); contains sparse charophytes; upper conformable contact corresponds to a pronounced color change from white to very pale orange micritic limestone below to brightly colored reddish-orange mudstone and siltstone above; query indicates uncertain identification on Navajo Ridge northwest of Brian Head peak, at the south end of the Red Hills, and near Willow Creek northeast of Paragonah.

As mapped on the southwest flank of the Sevier Plateau, the lower limestone interval is multi-hued mudstone, siltstone, and limestone that weathers to white and pink, subdued slopes. As such, its lower and upper contacts are difficult to pick except from a distance or on aerial photographs, and we are uncertain of correlation to exposures on the Markagunt Plateau.

The lower limestone unit attains its maximum thickness of about 300 feet (90 m) at Bryce Point in Bryce Canyon National Park (Bowers, 1990), but is only about 160 feet (50 m) thick to the north on the southwest flank of the Sevier Plateau. To the west, on the Markagunt Plateau, it is about 100 to 120 feet (30–35 m) thick in the upper reaches of Rock Canyon. Moore and others (1994) reported that their lower white limestone is generally 85 to 120 feet (26–36 m) thick, but as much as 180 feet (55 m) thick, in the Asay Bench quadrangle. This unit is only about 47 feet (14 m) thick at Cedar Breaks National Monument, where it is informally called the “lower white limestone” (Schneider, 1967; Rowley and others, in preparation), and about 30 feet (10 m) thick in the southern Red Hills (Threet, 1952).

Tcp **Pink member** (Eocene and Paleocene) − Alternating beds of varicolored and commonly mottled, pale-reddish-orange, reddish-brown, moderate-orange-pink, dark-yellowish-orange, and grayish-pink sandy and micritic limestone, calcite-cemented sandstone, calcareous mudstone, and minor pebbly conglomerate that weather to colluvium-covered ledgy slopes. **Limestone** is poorly bedded, microcrystalline, generally sandy with 2 to 20% fine-grained quartz sand, and is locally argillaceous; contains common calcite veinlets, calcite spar-filled vugs, calcite spar- and micrite-filled burrows, and stylolites; also contains sparse small bivalves and planispiral gastropods; many of these limestone beds are calcic paleosols (Mullett and others, 1988a, b; Mullett, 1989; Mullett and Wells, 1990). **Sandstone** is thick-bedded, fine- to coarse-grained, calcareous, locally cross-bedded quartz arenite that typically weathers to sculpted or fluted ledges that pinch out laterally; sandstone locally contains pebble stringers. **Mudstone** is generally moderate reddish orange, silty, calcareous, contains calcareous nodules, and weathers to earthy, steep slopes between ledges of sandstone and limestone. **Pebbly conglomerate** forms lenticular beds typically 5 to 15 feet (2–5 m) thick containing rounded quartzite, limestone, and chert pebbles, cobbles, and, locally, small boulders; conglomerate is uncommon on the Markagunt Plateau south of Parowan Canyon, but lower pink member strata are abundantly conglomeratic in the Red Hills and at the northwest edge of the Markagunt Plateau north of Parowan; at Sugarloaf Mountain west of Brian Head, several tens of feet of conglomerate (or several thinner beds within this interval) overlie the basal Claron limestone; Gregory (1951) and Bowers (1990) reported conglomeratic basal Claron strata on the Paunsaugunt Plateau. Upper, conformable contact corresponds to a pronounced color and lithologic change from brightly colored reddish-orange mudstone and siltstone below to white to very pale orange micritic limestone above.

Sinkholes are common in the pink member in the central Markagunt Plateau (Moore and others, 2004; Biek and others, 2011; Hatfield and others, 2010; Rowley and others, in preparation). Large sinkholes visible on 1:20,000-scale aerial photographs are plotted on the geologic map, and doubtless many smaller sinkholes are present. These sinkholes capture local runoff and serve to shunt shallow ground water rapidly down dip where it emerges as springs, including the large Mammoth and Asay Springs (Wilson and Thomas, 1964; Spangler, 2010).

The pink member is mostly nonfossiliferous and its age is poorly constrained as Eocene to Paleocene(?) (Goldstrand, 1994), but Nichols (1997) reported Late Cretaceous (Santonian?) pollen from gradationally underlying strata here mapped as Kwu south and west of Blowhard Mountain, and we recovered late Campanian to Maastrichtian pollen from this same interval, thus suggesting that the Claron Formation may be older than previously thought. Measurements from the map suggest that the pink member is about 1000 feet (300 m) thick at Cedar Breaks National Monument, similar to the measured thickness of Schneider (1967), who reported that the pink member there was 993 feet (303 m) thick (the lower 56 feet [17 m] of his section includes beds we assign to Kwu, thus the pink member there is 937 feet [286 m] thick), considerably less than the 1300 feet (400 m) reported in Sable and Maldonado (1997b). Strata that we include in the pink member are likely of similar thickness in more structurally complicated outcrops of the Red Hills (Threet, 1952, 1963). The pink member is about 600 feet (180 m) thick at Bryce Canyon National Park.

Tcpw **Pink member, limestone marker bed** (Eocene?) – White to very pale orange micritic limestone that may represent the northwest feather edge of either the lower or upper limestone units of the white member. Forms conspicuous ledge about 60 feet (18 m) thick near Mineral Canyon northeast of Paragonah, where it underlies a few hundred feet of Claron redbeds.

CRETACEOUS

Challenges of correlating Upper Cretaceous strata

Upper Cretaceous strata undergo significant west-to-east and north-to-south facies changes on the Markagunt and Paunsaugunt Plateaus, thus presenting significant challenges to correlation and mapping as described by Tilton (1991), Eaton and others (2001), Moore and Straub (2001), Moore and others (2004), and Rowley and others (in preparation). The lower part of this Upper Cretaceous section consists of coastal plain, marginal marine, and a westward-thinning wedge of marine strata deposited in a foreland basin east of the Sevier orogenic belt. Collectively, this sedimentary package, represented by the Dakota, Tropic, and Straight Cliffs Formations, was deposited during the Greenhorn Marine Cycle, a large-scale sea-level rise and fall recognized world-wide and that here corresponds to the maximum transgression of the Western Interior Seaway (figure 5) (see, for example, McGookey, 1972; Kauffman, 1984). This package of rock is overlain by Upper Cretaceous river and floodplain strata of the Wahweap Formation, and, locally on the Paunsaugunt Plateau, by newly discovered remnants of the Kaiparowits Formation.

Complicating this picture is the three-member Grand Castle Formation of the western Markagunt Plateau, originally inferred to be Paleocene in age. However, the lower two members are now known to be Upper Cretaceous and the upper member may be Upper Cretaceous as described below. Our mapping shows that the lower conglomerate member of the Grand Castle Formation is in fact the Drip Tank Member of the Straight Cliffs Formation (as originally suggested by Eaton and others, 2001; Moore and Straub, 2001; Lawton and others, 2003; and Eaton, 2006), and that the middle sandstone member of the Grand Castle Formation is in fact the capping sandstone member of the Wahweap Formation (as originally suggested by Pollock, 1999; and Lawton and others, 2003). Mapping coarse alluvial strata associated with major sequence boundaries has been the key to working out these lithostratigraphic correlations.

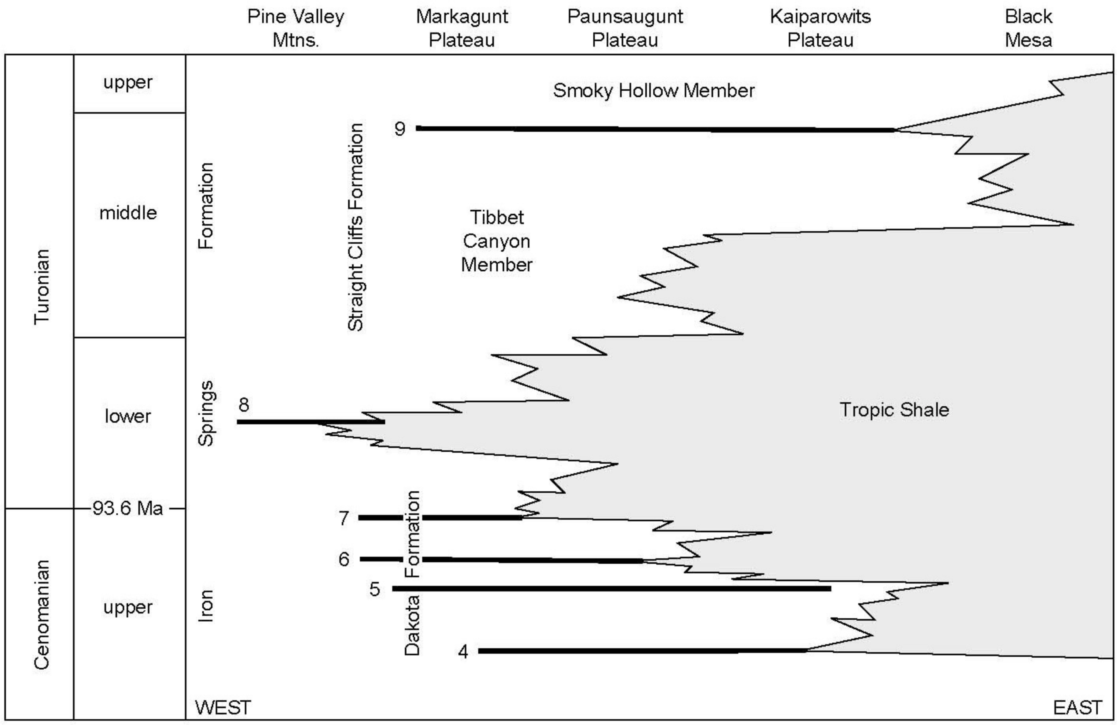

Figure 5. Strata of the Greenhorn Cycle (in gray), showing maximum flooding surface represented by the open-marine strata of the Tropic Shale and intermediate flooding surfaces represented by coal zones (4 to 9) that accumulated in brackish, estuarine environments near the western margin of the Western Interior Seaway. Note numerous smaller cycles superimposed on the larger Greenhorn Cycle, which are due to changes in subsidence, compaction, and climate. Note also the diachronous nature of the strata, meaning that the same facies differ in age from place to place. The upper Dakota Formation is equivalent in age to the lower part of the Tropic Shale exposed farther east—that is, they are the time-correlative coastal-plain and estuarine facies of the deeper water, offshore mud deposits of the Tropic Shale. Similarly, the Tibbet Canyon Member of the Straight Cliffs Formation is older in western exposures; it respresents eastward-prograding shoreline deposits that also are time-correlative with offshore Tropic muds. The Iron Springs Formation was deposited principally in braided-stream and floodplain environments of a coastal plain and is considered correlative with the Straight Cliffs Formation, Tropic Shale, and Dakota Formation. Simplified from Tibert and others (2003).

Ku **Grand Castle Formation (redefined), capping sandstone member of the Wahweap Formation, and Drip Tank Member of the Straight Cliffs Formation, undivided** (Upper Cretaceous) – Undivided along the northwest flank of the Markagunt Plateau between Red Creek and Little Creek where the three units are too thin to map separately at this scale; about 200 feet (60 m) thick.

Km **Cretaceous strata on the Markagunt Plateau** (Maastrichtian[?] to Santonian[?]) – Consists of yellowish-brown, commonly stained dark-reddish-brown, fine-grained sandstone and lesser interbedded, similarly colored mudstone and siltstone; bedding is thin to very thick and appears tabular from a distance; weathers to ledgy slope or cliff; outcrop habit and surficial color make it look like the pink member of the Claron Formation from a distance (figure 6); not mapped in Parowan Canyon and areas to the north, where basal Claron strata are conglomeratic and identification of this interval, if present, is uncertain; upper contact placed at the base of the first sandy limestone bed (calcic paleosol) of the pink member of the Claron Formation, following Moore and Straub (2001); about 200 feet (60 m) thick near State Highway 14 at the west edge of the Markagunt Plateau, but apparently thins to the north where it may be about 60 feet (20 m) thick in Parowan Canyon.

These Markagunt Plateau strata represent fluvial and floodplain environments apparently gradationally overlain by the Claron Formation. Like Moore and Straub (2001), we recognize no significant erosion beneath the Claron Formation at the west edge of the Markagunt Plateau, leading to uncertainty as to the age of this interval and the age of basal Claron strata. Nichols (1997) reported Late Cretaceous (Santonian?) pollen from strata we map as Kwu south and west of Blowhard Mountain, and we recovered late Campanian to Maastrichtian pollen from this same interval (Table 3). The apparently gradationally overlying basal Claron Formation is widely believed to be late Paleocene(?) (Goldstrand, 1994) based on one report of late Paleocene palynomorphs from basal Claron strata on the east flank of the Pine Valley Mountains and the gastropods *Viviparus trochiformis*, *Goniobasis*, and *Physa* from the pink Claron on the Table Cliff Plateau, eastern Pine Valley Mountains, and Bryce Point, respectively (Goldstrand, 1991).

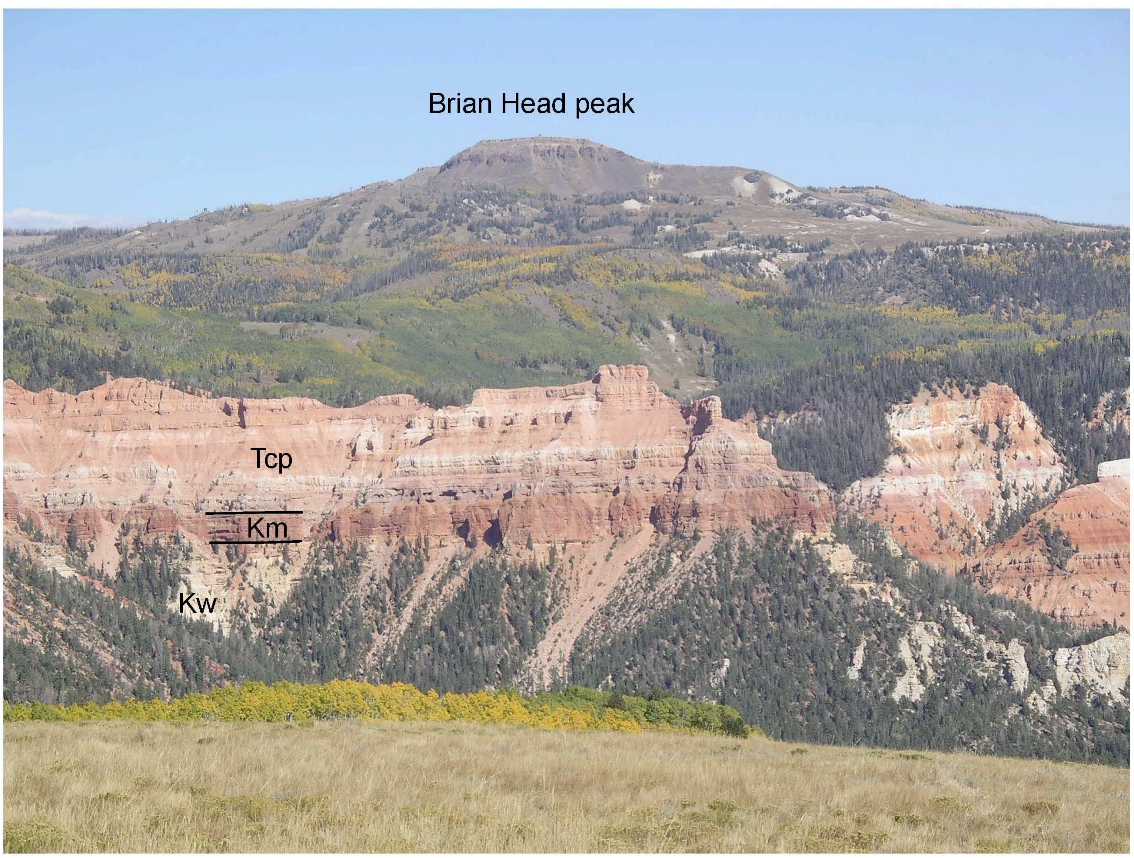

Figure 6. View east to Brian Head peak from High Mountain. Note sandstone cliff (Km), stained dark-reddish-brown from runoff from overlying pink member of the Claron Formation (Tcp). In most areas south of Parowan Canyon, the base of Km corresponds to the top of a thin pebble to small cobble conglomerate containing rounded quartzite and limestone clasts, although in some areas, as here, the conglomerate appears to be missing. Underlying yellowish-brown mudstone, siltstone, and sandstone are assigned to the Wahweap Formation (Kw). The base of the Claron Formation corresponds to the base of the first limestone bed, likely a calcic paleosol.

Kgc **Grand Castle Formation (redefined)** (Upper Cretaceous?, upper Campanian? to Maastrichtian?) – Light-gray and light-red massive conglomerate; clasts are well-rounded, pebble- to boulder-size quartzite, limestone, sandstone, and chert; cliff-forming in the Parowan Canyon area, where it locally weathers to form hoodoos similar to those of the Drip Tank Member (formerly lower conglomerate member of the Grand Castle Formation); thins dramatically south of Parowan Canyon where it is mapped as a poorly exposed marker bed. We also map Grand Castle Formation locally on the Paunsaugunt Plateau, where it is typically thin and poorly exposed at the base of the Claron Formation.

As much as about 200 feet (60 m) (Threet, 1952, 1963) to 300 feet (90 m) (Maldonado and Williams, 1993a) thick near Parowan Gap; Anderson and Dinter (2010) reported that there it is about 230 feet (70 m) thick. On the Markagunt Plateau, thins abruptly to the south from 183 feet (56 m) thick at the type area in First Left Hand Canyon southeast of Parowan (Goldstrand and Mullet, 1997) and the conglomerate may locally be absent south of Navajo Ridge (where it was not recognized in the measured sections of Goldstrand, 1991), but this interval is typically mantled in talus and colluvium that may obscure its presence. However, our mapping of Upper Cretaceous strata between Parowan and Cedar Canyons shows this conglomerate to be present at Sugarloaf Mountain (about 8 miles [13 km] south of Summit), in Last Chance Canyon (a tributary to Cedar Canyon) where it is about 25 feet (8 m) thick, in the upper reaches of Spring Creek Canyon below Cedar Breaks National Monument, west of Blowhard Mountain, and west of Navajo Lake where it is no more than a few feet thick. We thus conclude that though dramatically thinner than at its type section, the upper conglomerate member is present along the entire west margin of the Markagunt Plateau.

The upper contact with strata here mapped as Km on the Markagunt Plateau, and mapped as basal pink member of the Claron Formation in the Red Hills and northwestern Markagunt Plateau, appears gradational. On the Markagunt Plateau south of Parowan, the upper contact corresponds to the base of ledge- and cliff-forming, tabular bedded sandstone stained dark-reddish-brown from overlying Claron strata (see figure 6). Elsewhere, the upper contact corresponds to the top of the cliff-forming conglomerate, above which is interbedded reddish-brown siltstone, sandstone, mudstone, sandy limestone, and pebbly conglomerate of the Claron Formation.

The Grand Castle Formation (redefined) was deposited in a braided fluvial environment with paleoflow principally to the east to south-southeast, suggesting source areas in the Wah Wah, Blue Mountain, and Iron Springs thrust sheets of southwest Utah (Goldstrand and Mullett, 1997). Goldstrand and Mullett (1997) inferred a Paleocene age for their entire Grand Castle Formation based on distant correlations with Canaan Peak and Pine Hollow Formations on the Table Cliff Plateau, but we found evidence that the lower two members are Late Cretaceous and are thus reassigned as the Drip Tank Member of the Straight Cliffs Formation and the capping sandstone member of the Wahweap Formation as described below. The age of their upper conglomerate member of the Grand Castle Formation (here, the Grand Castle Formation [redefined]) is not well constrained, but we suggest that it is indeed Upper Cretaceous. A debris-flow deposit within the upper conglomerate member at its type section yielded Late Cretaceous (Santonian?) pollen that Goldstrand and Mullett (1997) interpreted as recycled from older strata. However, Nichols (1997) reported Late Cretaceous *Proteacidites* sp. pollen, which he interpreted as Coniacian and Santonian, from overlying beds here mapped as Kwu west and south of Blowhard Mountain, and we recovered late Campanian to Maastrichtian pollen from this same interval (Table 3).

In the northern Red Hills, the Grand Castle Formation (redefined) was earlier referred to as the conglomerate of Parowan Gap by Maldonado and Williams (1993a). However, like Goldstrand and Mullet (1997), we infer this interval to be their upper conglomerate member of the Grand Castle Formation because it is gradationally overlain by the pink member of the Claron Formation and their underlying middle Grand Castle sandstone is absent. Anderson and Dinter (2010) reported a 10- to 15-foot-thick (3–5 m) poorly sorted, matrix-supported conglomerate at the base of the Grand Castle that they informally called their conglomerate of Parowan Gap. They described this unit, which is apparently restricted to the hanging wall of the Iron Springs thrust, as distinct from overlying Grand Castle conglomerate, but lead-author Biek found mostly clast-supported conglomerate identical to the Grand Castle conglomerate at this horizon in his remapping of the Parowan Gap area. The basal few feet of Grand Castle Formation are locally iron stained throughout the Parowan Gap area, likely a result of a strong permeability contrast between underlying Upper Cretaceous strata and the overlying Grand Castle conglomerate.

unconformity

Kk **Kaiparowits Formation** (Upper Cretaceous, upper Campanian) – Bluish-gray, gray, and locally greenish- or brownish-gray, fine-grained, feldspathic, lithic sandstone, mudstone, and siltstone; contains locally abundant gastropods; typically poorly cemented, weathering to badland slopes whose bluish-gray hues contrast sharply with overlying pinkish Claron paleosols and underlying yellowish-brown Wahweap strata (figure 7); on the west side of the Paunsaugunt Plateau, however, commonly heavily forested and involved in large landslides, where it is recognized as far south as Proctor Canyon but presence of landslide deposits along its outcrop belt suggests that it may extend even farther south to Big Hollow; on the west flank of the plateau, base of formation is a bluish-gray smectitic mudstone as much as several meters thick, the slip surface for the landslides.

Incomplete sections of the Kaiparowits Formation are preserved about 3 miles (5 km) southeast of Flake Mountain where it is as much as about 450 feet (135 m) thick, and on the west flank of the Paunsaugunt Plateau where it is as much as about 200 feet (120 m) thick. The entire formation is about 2820 feet (860 m) thick in the Kaiparowits Basin east of the map area (Eaton, 1991; Doelling and Willis, 1999b; Roberts and others, 2005).

Figure 7. View north to tree-covered hill 8400 in the NW1/4 section 30, T. 35 S., R. 2 W. Here, about 450 feet (135 m) of lower Kaiparowits strata are preserved in the footwall of the Paunsaugunt fault, where they appear to dip slightly less steeply west than overlying Claron strata. Tcp = pink member, Claron Formation; Kk = Kaiparowits Formation; Kwcs = capping sandstone member, Wahweap Formation.

The Kaiparowits Formation was deposited as an eastward-prograding clastic wedge in a relatively wet, subhumid alluvial plain with periodic to seasonal aridity near the western margin of the Late Cretaceous Western Interior Seaway (Roberts, 2007). It is abundantly fossiliferous, with one of the richest and most diverse terrestrial vertebrate faunas of the Cretaceous Western Interior Basin (Roberts, 2007). Roberts and others (2005) reported four $^{40}Ar/^{39}Ar$ ages on sanidine from altered volcanic ashes that bracket the age of the formation in the Kaparowits Basin between 76.1 and 74.0 Ma, and that demonstrate extremely rapid sediment accumulation rates of 16 inches/kyr (41 cm/kyr). We report a new U-Pb age on zircon of 75.62 +3.08 -1.66 Ma for the bluish-gray smectitic mudstone at the base of the formation in Johnson Canyon on the west flank of the Paunsaugunt Plateau (UGS and A2Z, Inc., 2012; Gary Hunt, written communication, September 26, 2011); we also recovered late Campanian to Maastrichtian palynomorphs from this location (Table 3).

Tilton (1991, 2001a,b) first subdivided Upper Cretaceous strata of the southern Paunsaugunt Plateau, correctly noting the absence there of Kaiparowits Formation. In the area southwest of Tropic Reservoir, Bowers (1990) assigned light-brown, very fine grained sandstone and gray sandy mudstone (above the capping sandstone member of the

Wahweap Formation) to the Kaiparowits Formation, and although these beds are unlike typical bluish-gray feldspathic lithic Kaiparowits strata, they are correlative to strata we map as the upper unit of the Wahweap Formation (Kwu). Intermediate-scale maps of the southernmost Paunsaugunt and Markagunt Plateaus (Sable and Hereford, 2004; Doelling, 2008) incorrectly show Kaiparowits Formation on the Markagunt Plateau, and although unmapped, incorrectly suggest that it is intermittently present on the southern Paunsaugunt Plateau, which Tilton (2001a,b) clearly showed is not the case.

Ki **Iron Springs Formation** (Upper Cretaceous, Santonian or lower Campanian to Cenomanian) – Interbedded, ledge-forming, calcareous, cross-bedded, fine- to medium-grained sandstone and less-resistant, poorly exposed sandstone, siltstone, and mudstone present in the Red Hills at the west edge of the map area; the formation is variously colored grayish orange, pale yellowish orange, dark yellowish orange, white, pale reddish brown, and greenish gray and is locally stained by iron-manganese oxides; Liesegang banding is common in the sandstone beds; sandstone beds range from quartz arenite to litharenite (Fillmore, 1991; Goldstrand, 1992); the entire formation weathers to repetitive, thick tabular sandstone beds and thinner interbedded mudstone; lower part (in the upper plate of the Iron Springs thrust) contains numerous oyster coquina beds commonly 1 to 3 feet (0.3–1 m) thick; incomplete section is about 2500 feet (750 m) thick in the Red Hills (Maldonado and Williams, 1993a), but the entire formation is about 3500 to 4000 feet (1070–1220 m) thick in the Pine Valley Mountains (Cook, 1960).

Upper contact with the Grand Castle Formation (redefined) is difficult to map on the east side of the Red Hills due west of Parowan because of abundant Grand Castle-derived colluvium and faults. The Iron Springs Formation was deposited principally in braided-stream and floodplain environments of a coastal plain (Johnson, 1984; Fillmore, 1991; Eaton and others, 2001; Milner and others, 2006), and is typically correlated to the Dakota Formation, Tropic Shale, and Straight Cliffs Formation (Eaton, 1999; Eaton and others, 2001). Upper Cretaceous age is based on Goldstrand (1994) and an ash that is 712 feet (217 m) below the top of the formation in Parowan Canyon (here reassigned to the middle part of the Straight Cliffs Formation), which yielded an $^{40}Ar/^{39}Ar$ age of 83.0 ± 1.1 Ma (Eaton and others, 1999b). Lower Iron Springs strata (in the upper plate of the Iron Springs thrust) may be associated with the maximum transgression of the Greenhorn Sea of late Cenomanian or early Turonian age (Eaton and others, 1997; Eaton, 1999). Milner and others (2006) reported on dinosaur tracks in upper Iron Springs strata near Parowan Gap, and also noted a diverse assemblage of plant fossils, bivalves, gastropods, turtles, fish, and trace fossils suggestive of late Santonian to early Campanian age (Milner and Spears [2007] mistakenly reported an early Turonian age for these same beds).

Kws **Wahweap and Straight Cliffs Formations, undivided** (Upper Cretaceous) – Mapped in the Johns Valley area where it includes uppermost John Henry, Drip Tank, and basal Wahweap strata.

Kwcsd **Capping sandstone member of the Wahweap Formation and Drip Tank Member of the Straight Cliffs Formation, undivided** (Upper Cretaceous) – Mapped north of Red Creek (north of Paragonah) where too thin to map separately at this scale.

Wahweap Formation (Upper Cretaceous, lower? to middle Campanian) – Eaton (1991) divided the formation into four informal members in the Kaiparowits Basin, originally defined based principally on sandstone to mudstone ratios and fluvial architecture. In ascending order, these include his lower, middle, upper, and capping sandstone members. However, because of extensive vegetative cover and poor geomorphic expression in this map area, we map his lower three members simply as Wahweap Formation, undivided (Kw). The distinctive capping sandstone (Kwcs) is mapped separately, except on the south side of Johnson and Hillsdale Canyons due to poor exposure. Finally, we map two additional units that overlie the capping sandstone member on the west flank of the Paunsaugunt Plateau (Kwcg, Kwu). It is possible that Kwcg is simply an unusual facies of the capping sandstone member and that Kwu is better assigned to the base of the Kaiparowits Formation as discussed below.

The Wahweap Formation is mostly fine-grained sandstone, siltstone, and mudstone deposited in braided and meandering river and floodplain environments of a coastal plain (Tilton, 1991; Pollock, 1999; Lawton and others, 2003; Jinnah and others, 2011). Detrital zircon and provenance studies of Eaton's lower three members show that these rivers flowed longitudinally to the foreland basin and tapped sources in the Cordilleran magmatic arc in southern California or western Nevada and the Mogollon Highlands of southern Arizona, but that the capping sandstone member was deposited by transverse streams that tapped Mesozoic quartzose sandstones in the Sevier orogenic belt (Pollock, 1999; Lawton and others, 2003; Eaton, 2006; Jinnah and others, 2009). Thus the basal contact of the capping sandstone member represents an abrupt change in color, petrology, grain size, and fluvial style, documenting a major shift in depositional environments, from meandering to braided rivers, and in source areas, from arc to orogenic belt.

Jinnah and others (2009) reported an $^{40}Ar/^{39}Ar$ age of 80.6 ± 0.3 Ma (Campanian) on a devitrified volcanic ash located about 130 feet (40 m) above the base of the Wahweap Formation on the Kaiparowits Plateau, and further noted that the formation was deposited between about 81 and 76 Ma. Eaton and others (1999a) and Eaton (2006) reported enigmatic fossil mammals from near the base and top of the formation in Cedar Canyon that may be Campanian, and Lawton and others (2003) reported middle Campanian pollen from the upper part of the formation near Webster Flat, just southwest of Blowhard Mountain on the west rim of the Markagunt Plateau. We also recovered Santonian to Campanian pollen immediately below Kwcs near Webster Flat (Table 3).

Kw **Wahweap Formation, undivided** (Upper Cretaceous, lower? to middle Campanian) – Varicolored and mottled mudstone of brown, gray, reddish-brown, and pinkish hues, and yellowish-brown fine-grained sandstone and silty sandstone.

Exposures on Markagunt Plateau: Typically heavily vegetated and poorly exposed on the Markagunt Plateau, but likely equivalent to the lower, middle, and upper members as defined by Eaton (1991). The upper part, below the capping sandstone member, contains more sandstone than mudstone, also noted by Moore and Straub (2001) and Moore and others (2004). Measurements from the map show that the Wahweap Formation, excluding the capping sandstone member, is about 800 feet (245 m) thick below Cedar Breaks National Monument and south of Blowhard Mountain, and Moore and Straub (2001) measured 760 feet (230 m) of strata in Cedar Canyon that we assign to the Wahweap Formation (not including the capping sandstone member). A few tens of feet of lower Wahweap-like strata are present at the base of the capping sandstone member (formerly middle sandstone member of the Grand Castle Formation) in Parowan Canyon, illustrating a dramatic southward thickening of the unit south of Parowan Canyon. Eaton and others (1999a) and Moore and Straub (2001) initially proposed correlation of Cedar Canyon strata with early to middle Campanian Wahweap strata on the Kaiparowits Plateau.

Exposures on Paunsaugunt Plateau: Moderately well exposed and equivalent to the lower, middle, and upper members as defined by Eaton (1991). Collectively, these members thicken from east to west, from about 300 feet (90 m) thick about 6 miles (10 km) north-northeast of Tropic to in excess of 700 feet (210 m) thick on the west flank of the plateau. Thickness estimates of the Wahweap Formation on the west flank of the plateau are complicated by the Sand Pass fault, which cuts out the middle part of the formation. In Hillsdale Canyon, an exceptionally thick section of the upper Wahweap Formation (here mapped as Kwu, Kwcg, Kwcs, described below), is about 600 feet (180 m) thick, so we estimate that our entire Wahweap Formation is about 1200 to 1300 feet (360–400 m) thick on the west flank of the plateau.

Kwu **Upper unit** (Upper Cretaceous, middle? Campanian) – Consists of yellowish-brown, fine-grained sandstone and varicolored and mottled, reddish-brown, purplish-gray, and gray mudstone; sandstone forms two prominent ledges at the base and near the middle of the unit in Hillsdale Canyon on the west flank of the Paunsaugunt Plateau (figure 8); upper contact placed at the base of the first sandy limestone bed (calcic paleosol) or pebble to cobble conglomerate of the pink member of the Claron Formation, or at the base of bluish-gray, fine-grained, feldspathic, lithic sandstone, mudstone, and siltstone of the Kaiparowits Formation; as much as about 250 feet (75 m) thick in the Hillsdale Canyon area, but thins eastward under the Claron unconformity and is absent in exposures north-northeast of Tropic; as much as about 400 feet (120 m) thick south of Hillsdale Canyon, between Big Hollow and Proctor Canyon, where it may include strata elsewhere mapped as the gravelly unit (Kwcg).

Figure 8. View west-northwest to the entrance to Hillsdale Canyon, west side of Paunsaugunt Plateau. Here, the Wahweap Formation contains two additional units totaling about 400 feet (120 m) thick above the capping sandstone member (Kwcs) and below the Kaiparowits Formation (Kk). Kwcg denotes pebbly sandstone and mudstone that may be an unusual facies of the capping sandstone member, whereas Kwu denotes mudstone and sandstone that lacks pebbles and which may better be ascribed as a new basal facies of the Kaiparowits Formation. We include them in the Wahweap Formation simply because lithologically they resemble Wahweap strata rather than the distinctive bluish-gray feldspathic lithic sandstone and mudstone of the Kaiparowits Formation. This interval is absent from exposures in the Tropic Canyon quadrangle east of Johns Valley. Qms denotes landslide deposits derived from Claron Formation. Photo by Jeff Eaton.

Kwcg **Pebbly sandstone unit** (Upper Cretaceous, middle? Campanian) – Yellowish-brown, fine- to medium-grained sandstone with numerous, thin pebbly conglomerate stringers and lenticular beds as much as about 3 feet (1 m) thick; clasts are rounded quartzite, chert, and minor limestone; forms prominent cliff in the lower reaches of Hillsdale Canyon, but elsewhere weathers to ledgey slopes; mapped between Wilson Canyon (immediately north of Hillsdale Canyon) and Johnson Canyon, but was not definitely identified south of Johnson Canyon; appears to thin and become less pebbly eastward from Hillsdale Canyon and may pinch out north of Johnson Bench; as much as about 200 feet (60 m) thick in Hillsdale Canyon.

Kwcs **Capping sandstone member** (Upper Cretaceous, middle? Campanian) – White to very pale orange, locally iron stained, very fine to coarse-grained, mostly medium-grained, trough cross-bedded quartz arenite that "caps" the Wahweap Formation in its type area; upper part contains abundant pebble stringers and conglomeratic beds with rounded quartzite, dolostone, chert, and limestone clasts; clasts are typically about 1 inch (2.5 cm) in diameter but as large as 2 to 3 inches (5–7.5 cm), and include common reddish-brown and purple quartzite clasts, unlike underlying Drip Tank strata; quartz grains are typically well rounded and commonly frosted, recycled from Mesozoic eolianites (Pollock, 1999; Lawton and others, 2003); locally contains carbonized or petrified plant debris, small mudstone rip-up clasts, iron concretions, and soft-sediment deformation features; typically poorly cemented, forming distinctive white, manzanita-covered slope-and-bench topography; attains its maximum thickness of 277 feet (85 m) at the type section of the equivalent and now superceded middle member of the Grand Castle Formation in First Left Hand Canyon southeast of Parowan, and elsewhere, map patterns show that the member is about 200 feet (60 m) thick.

Among the best exposures of the capping sandstone on the Markagunt Plateau are those about 2 miles (3.5 km) southwest of Parowan, at the mouth of Summit Creek canyon, at the type area in First Left Hand Canyon (southeast of Paraowan), and in a State Highway 14 road cut west of Blowhard Mountain. We discovered Campanian to Santonian palynomorphs and a theropod dinosaur track (the latter found by Eric Roberts, formerly with Southern Utah University and now at James Cook University, Australia) in the lower part of the interval in an unnamed canyon about 2 miles (3 km) southwest of Parowan, confirming our suspicion of a Late Cretaceous age for this member on the Markagunt Plateau (Hunt and others, 2011).

As defined in the Kaiparowits Basin, includes yellowish-brown, fine-grained sandstone locally with thin lenses of mudstone (similar to parts of Eaton's lower Wahweap strata), but as mapped here restricted to distinctive white quartz arenite facies. Equivalent to the middle member of the Grand Castle Formation as suggested by Lawton and others (2003), confirmed by this mapping, and supported by preliminary detrital zircon analyses (Johnson and others, 2011), who examined detrital zircon populations of three samples from the Markagunt and Paunsaugunt Plateaus and concluded that they represent sediments of a braided stream system that drained thrust sheets of the Sevier orogenic belt to the west. Goldstrand and Mullett (1997) and Lawton and others (2003) also showed that the member was deposited in a braided fluvial environment with a paleoflow direction principally to the east to south-southeast, suggesting source areas in Navajo Sandstone exposed in the upper plate of the Iron Springs thrust, now exposed in the Red Hills.

Along much of the west flank of the Markagunt Plateau south of Parowan Canyon, the capping sandstone member is commonly covered by talus and colluvium derived from overlying Claron Formation. There, we used a dashed lower contact to indicate our uncertainty as to its true thickness. Our mapping confirms the finding of Goldstrand and Mullet (1997), who first correlated the sandstone at the Websters Flat turnoff with their middle sandstone member of the Grand Castle Formation.

Straight Cliffs Formation (Upper Cretaceous, late Santonian to Turonian) – Peterson (1969) divided the Straight Cliffs Formation into four members in the Kaiparowits Basin: in ascending order, the Tibbet Canyon, Smoky Hollow, John Henry, and Drip Tank Members. Several geologists mapped these members (separately or as lumped upper and lower Straight Cliffs strata) on the Paunsaugunt Plateau, including Tilton (1999, 2001a,b), Doelling and Willis (1999a), Sable and Hereford (2004), and Doelling (2008), and we described above (see Challenges of correlating Upper Cretaceous strata) the difficulty encountered in early attempts to carry this nomenclature westward into the Markagunt Plateau. On the Markagunt Plateau, we map the Tibbet Canyon Member where it forms bold cliffs at the west and south margins of the plateau; we lump the Smoky Hollow and John Henry Members since the intervening Calico bed is typically poorly developed; and we map the Drip Tank Member, which is the same interval as the "old" lower conglomerate member of the Grand Castle Formation, as originally suggested by Eaton and others (2001), Moore and Straub (2001), Lawton and others (2003), and Eaton (2006). On the Paunsaugunt Plateau, we map the Tibbet Canyon and Smoky Hollow Members together following Bowers (1990) and Doelling and Willis (1999a), and map the John Henry and Drip Tank Members separately.

The Straight Cliffs Formation forms an overall regressive sequence following the last marine incursion of the Western Interior Seaway (see, for example, Eaton and others, 2001; Moore and Straub, 2001; Tibert and others, 2003). The Tibbet Canyon Member represents initial progradational (overall regressive) strata of the Greenhorn Cycle deposited in shoreface, beach, lagoonal, and estuarine environments adjacent to a coastal plain (Laurin and Sageman, 2001; Tibert and others, 2003). The overlying Smoky Hollow, John Henry, and Drip Tank Members were deposited in fluvial and floodplain environments of a coastal plain (Peterson, 1969; Eaton and others, 2001).

Ksd **Drip Tank Member** (Upper Cretaceous, late Santonian) – On the Paunsaugunt Plateau, Drip Tank strata are white to light-gray, fine- to medium-grained quartzose sandstone, and, in the upper part of the unit, pebbly sandstone and pebbly conglomerate; very thick bedded with prominent cross-stratification; clasts are subrounded to rounded, white and gray quartzite, gray Paleozoic limestone, and black chert, and lack the reddish-brown and purple quartzite clasts found in capping sandstone strata; locally iron stained and locally contains casts of tree limbs; lower sandstone forms distinctive, manzanita-covered slopes and saddles, but upper part of unit tends to forms cliffs and ledges; upper contact with the Wahweap Formation appears to be conformable and corresponds to the top of a white sandstone and pebbly sandstone, above which is yellowish-brown, fine-grained sandstone and lesser interbedded, varicolored and mottled mudstone of brown, gray, reddish-brown, and pinkish hues; as mapped, restricted to the white quartz arenite and pebbly conglomerate facies and thus ranges from about 100 to 200 feet (30–60 m) thick on the Paunsaugunt Plateau; Tilton (2001a) reported that the member is 185 to 215 feet (56–66 m) thick on the southern Paunsaugunt Plateau, immediately south of the map area in the Alton quadrangle.

On the Markagunt Plateau, the Drip Tank Member (formerly lower conglomerate member of the Grand Castle Formation) is a massive, cliff-forming, light-gray conglomerate with well-rounded, pebble- to boulder-sized clasts of quartzite, limestone, and minor sandstone and chert. It is 135 feet (41 m) thick at the type section in First Left Hand Canyon southeast of Parowan (Goldstrand and Mullet, 1997), and of similar thickness southwest to Sugarloaf Mountain (about 3 miles [5 km] west of Brian Head). South of this area, however, the lower conglomerate thins irregularly southward, ranging from a few feet thick to nearly 100 feet (30 m) thick, and locally appears as two conglomerate intervals separated by a few feet to a few tens of feet of yellowish-brown, fine-grained sandstone or variegated mudstone. The Drip Tank Member typically overlies stacked or amalgamated sandstone beds, but locally, as along Ashdown Creek in the southwest corner of the map area, overlies variegated mudstone. On the northern Markagunt Plateau, the member locally weathers to form conically shaped hoodoos that resemble old-fashioned beehives known as bee skeps, but south of Summit it forms a resistant ledge in the upper reaches of Summit Creek canyon and the upper reaches of Pickering Creek canyon.

Tilton (1991) described the Drip Tank Member as the most prominent and important marker horizon in the Upper Cretaceous section on the southern Paunsaugunt Plateau, but we find that it is remarkably similar in lithology and outcrop habit to the capping sandstone member of the Wahweap Formation. The Drip Tank was deposited by east- and northeast-flowing braided streams (Tilton, 1991, 2001a,b; Lawton and others, 2003); its age is constrained by the ages of enclosing well-dated strata.

unconformity

Ksjs **John Henry and Smoky Hollow Members, undivided** (Upper Cretaceous, Santonian[?] to Turonian) – Undivided on the Markagunt Plateau, where the Calico bed is poorly exposed and apparently only locally well developed; see map unit descriptions below; combined unit is about 1250 to 1350 feet (m) thick on the Markagunt Plateau (Eaton and others, 2001; Moore and Straub, 2001).

The striking difference in facies and outcrop habit of correlative Upper Cretaceous strata between Cedar and Parowan Canyons has long been noted (see, for example, Eaton and others, 2001). Only about the upper 1000 feet (300 m) of strata previously assigned to the Iron Springs Formation is exposed in Parowan Canyon, where it is characterized by repetitive ledge-forming tabular sandstone beds and interbedded, slope-forming mudstone. Equivalent strata to the south in Cedar Canyon, the John Henry Member of the Straight Cliffs Formation, are characterized by generally poorly exposed, typically slope-forming, stacked or amalgamated sandstone and relatively little mudstone; mudstone, however, dominates the lower part of the John Henry in Cedar Canyon, which is apparently not exposed in Parowan Canyon.

Ksj **John Henry Member** (Upper Cretaceous, Santonian to upper Coniacian) – Slope-forming, variegated, gray, brown, and reddish-brown mudstone and thin- to thick-bedded, grayish-orange to yellowish-brown, fine-grained subarkosic sandstone; forms ledgy slopes; sandstone is commonly bioturbated and locally stained by iron-manganese oxides; stacked or amalgamated sandstone beds make up most of the upper part of the unit; upper contact corresponds to a break in slope at the base of the Drip Tank Member (on the Markagunt Plateau, formerly the lower conglomerate of the Grand Castle Formation); biotite from an ash bed about 800 feet (245 m) above the base of the member in Cedar Canyon yielded an $^{40}Ar/^{39}Ar$ age of 86.72 ± 0.58 Ma (early Coniacian) (Eaton, 1999; Eaton and others, 1999b); Eaton and others (1999b) also reported an $^{40}Ar/^{39}Ar$ age of 83.0 ± 1.1 Ma for an ash bed that is 712 feet (217 m) below the top of the member in Parowan Canyon; about 900 to 1000 feet (275–300 m) thick in Cedar Canyon (Moore and Straub, 2001), 800 to 1100 feet (240–335 m) thick at Bryce Canyon National Park (Bowers, 1990), and about 670 feet (200 m) thick at the south end of the Paunsaugunt Plateau (Tilton, 2001a).

Ksjc **John Henry Member, lower part** (Upper Cretaceous, Santonian to upper Coniacian) – White to light-gray, fine- to medium-grained, cross-bedded sandstone and pebbly conglomerate likely equivalent to the Calico bed; mapped east of the Paunsaugunt fault; 80 to 100 feet (25–30 m) thick.

unconformity

Ksht **Smoky Hollow and Tibbet Canyon Members, undivided** (Upper Cretaceous, Turonian) – Undivided on the east flank of the Paunsaugunt Plateau following Bowers (1990), where the combined members are about 240 to 300 feet (70–90 m) thick.

Ksh **Smoky Hollow Member** (Upper Cretaceous, middle Turonian) – Smoky Hollow strata are not mapped separately given the difficulty of separating typically poorly exposed Smoky Hollow and John Henry strata where the intervening Calico bed is not well developed. Smoky Hollow strata are slope-forming, brown and gray mudstone, shale, and interbedded yellowish-brown fine-grained sandstone; lower part contains a few thin coal beds, common carbonaceous shale, and several thin oyster coquina beds; upper contact corresponds to the top of the Calico bed, a stacked series of fluvial channel deposits of white to light-gray, fine- to medium-grained sandstone and conglomeratic sandstone; Smoky Hollow strata are middle to upper Turonian based on a diverse assemblage of mollusks, benthic foraminifera, and ostracods from exposures in Cedar Canyon (Eaton and others, 2001; Tiebert and others, 2003); Moore and Straub (2001) assigned 313 feet (95 m) of strata in Cedar Canyon as likely equivalent to the Smoky Hollow Member; Eaton and others (2001) measured 364 feet (110 m) of strata that likely belong to the Smoky Hollow Member in Cedar Canyon, the lower 167 feet (54 m) of which are brackish and an order of magnitude thicker than equivalent brackish strata on the Kaiparowits Plateau, reflecting greater subsidence rates in the western part of the foredeep basin; not including the Calico bed, Bowers (1990) assigned 200 to 250 feet (60–75 m) of strata to the Smoky Hollow Member at Bryce Canyon

National Park, and 80 to 100 feet (25–30 m) to the Calico bed itself; Tilton (2001a), however, reported that the entire Smoky Hollow Member is just 125 to 140 feet (40–45 m) thick at the south end of the Paunsaugunt Plateau.

Moore and Straub (2001, their subunit 4 of interval A) suggested that the Calico bed may be present in Cedar Canyon about 285 feet (87 m) above the base of the formation. Subunit 4 is sandstone about 30 feet (9 m) thick but it is not distinctive, in as much as it lacks pebbles and we were unable to use this bed as a marker horizon. However, we did locally map a thin pebble conglomerate about 330 feet (100 m) above the base of the formation on the Kolob Terrace in the southwest corner of the map area, which may be the Calico bed. Bobb (1991) noted that sediments of the Calico bed were deposited by braided and meandering streams that tapped both the Sevier orogenic belt and the Mogollon Highlands.

Kst **Tibbet Canyon Member** (Upper Cretaceous, Turonian) **–** Grayish-orange to yellowish-brown, generally medium- to thick-bedded, planar-bedded, fine- to medium-grained quartzose sandstone and minor interbedded, grayish-orange to gray mudstone and siltstone; locally contains pelecypods, gastropods, and thin to thick beds of oyster coquina; forms bold cliffs in Cedar Canyon and in the West and East Forks of Braffits Creek south of Summit, and a prominent though thinner cliff on the east flank of the Paunsaugunt Plateau; upper contact corresponds to a pronounced break in slope and is placed at the top of a coquinoid oyster bed and base of overlying thin coal and carbonaceous shale interval that caps the member; forms the riser of the Gray Cliffs part of the Grand Staircase; represents initial progradational (overall regressive) strata of the Greenhorn Cycle deposited in shoreface, beach, lagoonal, and estuarine environments adjacent to a coastal plain (Laurin and Sageman, 2001; Tibert and others, 2003); thins eastward from about 650 to 800 feet (200–245 m) thick on the west flank of the Markagunt Plateau, 120 to 160 feet (37–50 m) thick at the south end of the Paunsaugunt Plateau (Tilton, 2001a,b), and only 40 to 50 feet (12–15 m) thick on the east flank of the Paunsaugunt Plateau.

Ktd **Tropic Shale and Dakota Formation, undivided** (Upper Cretaceous, Turonian to Cenomanian) **–** Undivided in Cedar Canyon where the Tropic Shale is a few feet to at most a few tens of feet thick.

Kt **Tropic Shale** (Upper Cretaceous, Turonian to Cenomanian) **–** Gray to olive-gray, very thin bedded shale and silty shale in eastern exposures, but thins dramatically westward where it is dark-gray and yellowish-brown sandy mudstone, silty fine-grained sandstone, and minor shale; weathers to form badlands in the type area near Tropic; on the Markagunt Plateau, the base of the formation is locally characterized by a lag of septarian nodules, and Titus and others (2005) noted that the nodules are characteristic of the lower and middle parts of the formation east of the Paunsaugunt Plateau; numerous smectitic volcanic ash beds occur throughout the formation (Titus and others, 2005); contains locally abundant, well-preserved fossils, including ammonites, inoceramid and mytiloidid bivalves, gastropods, and oysters, as well as vertebrate fossils of sharks, fish, marine turtles, and plesiosaurs, all indicative of open shallow-marine environment (see, for example, Eaton and others, 2001; Titus and others, 2005); on the Markagunt Plateau, typically poorly exposed, but forms subtle, vegetated slope at the base of the Straight Cliffs Formation and above the prominent "sugarledge sandstone" (Cashion, 1961) at the top of the Dakota Formation; upper, conformable contact placed at the base of the cliff-forming, planar beds of the Straight Cliffs Formation (figure 9); deposited in shallow-marine environment dominated by fine-grained clastic sediment, marking the maximum incursion of the Western Interior Seaway (Tibert and others, 2003); age well constrained from ammonite and inoceramid biostratigraphy and dated interbedded volcanic ash beds (see, for example, Titus and others, in press); thins westward across the map area, from about 700 feet (215 m) thick east near Tropic, to 40 feet (12 m) thick in the southwest part of the map area, to just a few feet thick in Cedar Canyon; Doelling and Willis (1999) reported that it is 600 to 900 feet (180–275 m) thick in the southeast corner of the Panguitch 30' x 60' quadrangle.

Ktu **Tropic Shale, upper unit** (Upper Cretaceous, Turonian) **–** Gray and brown silty shale, mudstone, and fine-grained sandstone that forms an interval transitional to the overlying Tibbet Canyon Member of the Straight Cliffs Formation; mapped north of Tropic where it forms a light-colored slope nearly 200 feet (60 m) thick below the prominent Tibbet ledge.

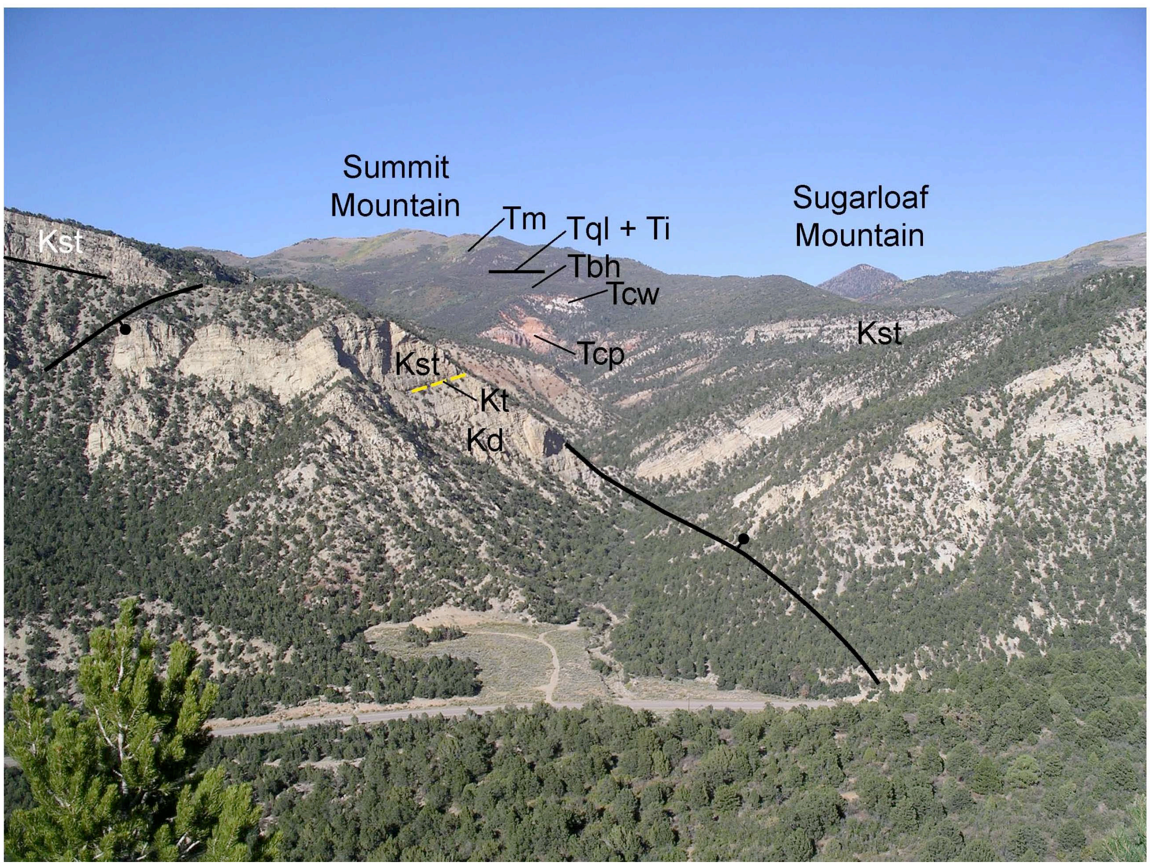

Figure 9. View north into Maple Canyon, tributary to Cedar Canyon at the west edge of the Markagunt Plateau; State Highway 14 is in the foreground. The Tropic Shale is represented by a thin, dark-gray mudstone and siltstone that forms a slope between ledge- and cliff-forming sandstone of the Dakota Formation (Kd) and the Tibbet Canyon

Member of the Straight Cliffs Formation (Kst). The thin slope of Tropic represents the maximum incursion of the Western Interior Seaway in Late Cretaceous (early Turonian) time. Underlying Dakota strata—deposited as an overall transgressive unit of floodplain, estuarine, lagoonal, and swamp environments of a coastal plain—record the encroachment of that seaway, whereas overlying Tibbet Canyon strata were deposited in an overall progradational sequence of marginal-marine and beach environments following retreat of the Western Interior Sea.

Several normal faults cut strata of Maple Canyon, which partly follows the south end of the Summit Mountain graben. Tcp (pink member) and Tcw (white member) of the Claron Formation; regional ash-flow tuffs of the Leach Canyon Formation (Tql) and Isom Formation (Ti), which overlie the vegetated Brian Head Formation (Tbh), are unconformably overlain by the Markagunt Megabreccia (Tm).

Kd **Dakota Formation** (Upper Cretaceous, Cenomanian) **–** Interbedded, slope- and ledge-forming sandstone, siltstone, mudstone, claystone, carbonaceous shale, coal, and marl; sandstone is yellowish brown or locally white, thin to very thick bedded, fine to medium grained; includes several prominent cliff-forming sandstone beds each several tens of feet thick in the upper part of the formation, the upper one of which may correspond to the "sugarledge sandstone" of Cashion (1961); mudstone and claystone are gray to yellowish brown and commonly smectitic; the Dakota Formation contains two significant coal zones on the Paunsaugunt Plateau, the lower Bald Knoll zone and the upper Smirl zone (Doelling, 1972; Quick, 2010); oyster coquina beds, clams, and gastropods, including large *Craginia* sp., are common, especially in the upper part of the section; thin marl beds above the "sugarledge sandstone" locally contain small, distinctive gastropods with beaded edge (*Admetopsis* n. sp. indicative of a latest Cenomanian brackish water environment [Eaton and others, 2001]); thins dramatically eastward, from about 1300 to 1400 feet (400–425 m) thick on the Markagunt Plateau at the south end of Jones Hill west of Maple Canyon, to about 80 to 275 feet (24–85 m) thick on the Paunsaugunt Plateau (Doelling and Willis, 1999; Tilton, 2001a).

Dakota strata are typically poorly exposed and involved in large landslides on the Markagunt Plateau. Most workers divide the Dakota Formation into three members, the lower one of which we re-assign to the Cedar Mountain Formation and the upper two of which we combine given the difficulty of mapping their mutual contact. The upper contact with the Tropic Shale is conformable. On the Markagunt Plateau, the contact corresponds to the top of the thin marl beds overlying the "sugarledge sandstone," whereas on the Paunsaugunt Plateau, it is placed at the top of the highest coal bed, which has locally burned, creating baked mudstone (clinker) at this horizon. The Dakota Formation is not correlative with the type Dakota in Nebraska, but the term is used loosely in Utah for deposits of an overall transgressive sequence below the Tropic Shale, the lower part of which was deposited in floodplain and river environments, whereas the upper part represents estuarine, lagoonal, and swamp environments of a coastal plain (Gustason, 1989; Eaton and others, 2001; Laurin and Sageman, 2001; Tibert and others, 2003). Gustavson (1989), based in part on study of exposures in Cedar Canyon, correlated fluvial packages of the Dakota with orbital cycles of marine sedimentation of the deeper parts of the Western Interior Sea. Laurin and Sageman (2001) expanded on that work, constructing a high-resolution temporal and stratigraphic framework of middle

Cretaceous marginal-marine deposits—they documented changes in shoreline position and also linked these changes to rhythmic, Milankovitch-driven deposition of marine limestone of the Western Interior Seaway. Invertebrate and palynomorph fossil assemblages in the Dakota indicate shallow-marine, brackish, and fresh-water deposits of Cenomanian age (Nichols, 1997; Eaton, 2009); Dyman and others (2002) reported an early Cenomanian $^{40}Ar/^{39}Ar$ age of 96.06 ± 0.30 Ma from middle Dakota strata about 2 miles (4 km) south of Tropic.

Kcm **Cedar Mountain Formation** (Cretaceous, Cenomanian to Albian) **–** Consists of a basal pebble conglomerate overlain by brightly colored variegated mudstone in Cedar Canyon. Mudstone is variegated gray, purplish-red, and reddish-brown, distinctly different from the gray and yellowish-brown hues of overlying Dakota strata; clay is smectitic and weathers to "popcorn-like" soils; includes minor light-gray to dark-yellowish-brown, fine- to medium-grained channel sandstone. Basal conglomerate is grayish brown and typically poorly cemented and non-resistant; clasts are subrounded to rounded, pebble- to small-cobble-size quartzite, chert, and limestone; red quartzite clasts are common; entire formation is about 60 feet (18 m) thick in Cedar Canyon, and the conglomerate ranges from less than one foot (0.3 m) to about 10 feet (3 m) thick.

Except for the thin conglomerate ledge at its base, weathers to generally poorly exposed slopes covered with debris from the overlying Dakota Formation. Upper contact is poorly exposed and corresponds to a color and lithologic change, from comparatively brightly colored smectitic mudstone below to gray and light-yellowish-brown mudstone and fine-grained sandstone above (figures 10 and 11), but regionally, the Cedar Mountain Formation is unconformably overlain by the Dakota Formation (see, for example, Kirkland and others, 1997). Volcanic ash from correlative strata on the Kolob Plateau yielded a single-crystal $^{40}Ar/^{39}Ar$ age of 97.9 $\pm$ 0.5 Ma on sanidine (Biek and Hylland, 2007), pollen analyses indicate an Albian or older age (Doelling and Davis, 1989; Hylland, 2010), and Dyman and others (2002) obtained an $^{40}Ar/^{39}Ar$ age of 101.7 $\pm$ 0.42 Ma (latest Albian) on equivalent strata near Gunlock, Utah. Additionally, palynomorphs from a thin mudstone interval, including rare occurrences of *Trilobosporites humilis* and possibly *Pseudoceratium regium*, collected in Cedar Canyon immediately to the west of the map area (NW1/4 NW1/4 SE1/4 section 17, T. 36 S., R. 10 W., Cedar City 7.5′ quadrangle) suggest a late Albian age for this horizon (Mike Hylland, Utah Geological Survey, unpublished data, November 9, 2001). The Cedar Mountain Formation was deposited in floodplain environment of a broad coastal plain (Tschudy and others, 1984; Kirkland and others, 1997; Cifelli and others 1997; Kirkland and Madsen, 2007). This interval was previously mapped as the lower part of the Dakota Formation, but the lithology, age, and stratigraphic position of these beds suggest correlation to the Cedar Mountain Formation (Biek and others, 2003; Biek and Hylland, 2007; Biek and others, 2009; and Hylland, 2010). Specifically, the mudstone interval appears to be time-correlative with the Mussentuchit Member of the Cedar Mountain Formation of central and eastern Utah.

The basal conglomerate is part of the relatively thin but widespread Lower Cretaceous gravels that once formed a broad alluvial plain over most of the Western Interior. As noted in the classic paper by Heller and Paola (1989), the distribution of these gravels is believed to reflect regional thermal uplift associated with Jurassic-

Cretaceous magmatism in the hinterland, immediately prior to onset of thrusting in the Sevier orogenic belt and creation of sediment-trapping foredeep and backbulge basins. Detrital zircon studies of Hunt and others (2011) showed that the clasts were largely derived from Ordovician to Devonian strata in the Sevier thrust belt, and suggested correlation with the Short Canyon Conglomerate of central Utah (Doelling and Kuehne, in press).

Figure 10. View northwest of the Cedar Mountain Formation exposed in Cedar Canyon near the west edge of the map area. Base of Cedar Mountain Formation (Kcm) is marked by a thin pebble conglomerate and overlying dark-gray bentonitic ash; note thin, lenticular channel sandstone near base of Cedar Mountain strata and bleached upper part of Winsor Member of the Carmel Formation (Jcw). Co-op Creek Limestone Member of the Carmel Formation (Jcc) is exposed at road level along State Highway 14; Crystal Creek strata are hidden from view; Paria River Member (Jcp). View west down Cedar Canyon; outcrop is in the SW1/4NE1/4NW1/4 section 21, T. 36 S., R. 10 W.

Figure 11. View north of the Cedar Mountain Formation (Kcm) and enclosing units in the SW1/4SE1/4SW1/4 section 16, T. 36 S., R. 10 W. Swelling mudstone of light-gray, reddish-brown, and purplish hues contrast sharply with yellowish-brown and olive-gray mudstone of overlying Dakota Formation (Kd). About 40 feet (12 m) above the base of the Dakota Formation, a ledge-forming 20-foot-thick (6 m) pebbly sandstone and conglomerate with rounded quartzite and black chert clasts is present. Jcw = Winsor Member of Carmel Formation.

Unconformity (K). No rocks of late Middle Jurassic to middle Early Cretaceous age are preserved in southwest Utah. This is because during this time, the back-bulge basin that developed in front of the Sevier orogenic belt had migrated eastward, and much of Utah was a forebulge high, a broad, gentle uplift that was high enough to undergo a prolonged period of modest erosion (see, for example, Willis, 1999). In this area, this 60-million-year-long gap in the rock record is marked by a bleached zone at the top of the Winsor Member of the Carmel Formation (figure 10). The Cretaceous unconformity cuts down section to the west, where, on the south flank of the Pine Valley Mountains, first Winsor, then Paria River, and finally Crystal Creek strata are completely eroded away, so that at Gunlock the Cedar Mountain Formation rests upon the Co-op Creek Limestone, the lower member of the Carmel Formation (Biek and others, 2009).

JURASSIC

Jh **Henrieville Sandstone** (Middle Jurassic) – White to pale-yellow, fine- to medium-grained, poorly sorted, calcareous sandstone, siltstone, claystone, and shale; lower part of formation is planar-bedded siltstone, claystone, and shale of probable fluvial origin, whereas upper part is mostly cross-bedded sandstone of eolian origin; entire unit forms cliff or steep slope that is just a few tens of feet thick southeast of Cannonville, but is as much as about 230 feet (70 m) thick in the adjacent Escalante 30' x 60' quadrangle (Doelling and Willis, 1999b); Baer and Steed (2010) reported that the Henrieville Sandstone is 65 feet (20 m) thick at Kodachrome Basin State Park immediately southeast of the map area.

Thompson and Stokes (1970) noted that the Henrieville Sandstone, the type section of which is immediately east of the map area near Henrieville, is truncated westward under the Cretaceous unconformity, and they envisioned that it unconformably overlies the Escalante Member of the Entrada Sandstone. It is mapped here following Doelling and Willis (1999a). Thompson and Stokes (1970) suggested that the Henrieville Sandstone may correlate with the Salt Wash Member of the Morrison Formation; Peterson (1988) suggested that it is simply a bleached upper part of the Escalante Member of the Entrada Sandstone.

Je **Entrada Sandstone** (Middle Jurassic) – Consists of upper, middle, and lower members, which here are described following Doelling and Willis (1999a) but not mapped separately; the upper, Escalante Member is white, light-gray, pale-orange, and yellow-brown, fine- to coarse-grained, massive, high-angle cross-bedded, cliff-forming sandstone; the middle, Cannonville Member is mostly reddish-brown and gray silty sandstone and sandy siltstone that forms a banded slope; the lower, Gunsight Butte Member is mostly reddish-brown, fine-grained, cross-bedded, silty sandstone that commonly forms cliffs. Baer and Steed (2010) reported that the Escalante Member is 110 feet (34 m) thick, the Cannonville Member is 138 feet (42 m) thick, and the Gunsight Butte Member is 280 feet (85 m) thick in nearby Kodachrome Basin State Park; collectively, the formation there is about 530 feet (160 m) thick.

The Entrada Sandstone records deposition in tidal-flat, sabkha, and coastal dune environments (Peterson, 1988, 1994). At and near Kodachrome Basin, the Gunsight Butte Member is renowned for its sedimentary breccia pipes, which are thought to have formed as fluid escape structures from overpressured, underlying Carmel strata in Middle Jurassic time, probably prior to deposition of the Henrieville Sandstone (Baer and Steed, 2010).

Jc **Carmel Formation, undivided** (Middle Jurassic) – Undivided in the Parowan Gap area following Maldonado and Williams (1993a), where it is mostly light-gray micritic limestone and lesser yellowish-gray and reddish-brown fine- to medium-grained sandstone likely of the Co-op Creek Limestone and Crystal Creek Members; about 800 feet (250 m) thick.

Nomenclature of the Carmel Formation follows that of Doelling and Davis (1989) and Sprinkel and others (2011a). The Carmel Formation was deposited in a shallow inland sea of a back-bulge basin, and together with the underlying Temple Cap Formation, provides the first clear record of the effects of the Sevier orogeny in southwestern Utah (Sprinkel and others, 2011). Middle Jurassic age is from Imlay (1980) and Sprinkel and others (2011a). Measured thicknesses in Cedar Canyon are from Doug Sprinkel (Utah Geological Survey, written communication, June 22, 2010).

Sprinkel and others (2011a) noted that several oil and gas exploration wells in the eastern part of the map area encountered Middle Jurassic salt at depth and so these strata are best assigned to the Twelvemile Canyon Member of the Arapien Formation. Carmel and Arapien strata thus interfinger at depth under the eastern Markagunt Plateau and Sevier valley. For simplicity, we use the Carmel Formation for this entire interval on the cross sections.

Jcw **Winsor Member** (Middle Jurassic, Callovian to Bathonian) – Light-reddish-brown, fine- to medium-grained sandstone and siltstone; uppermost beds typically bleached white under the Cretaceous unconformity; poorly cemented and so weathers to vegetated slopes, or, locally, badland topography; upper contact is at the base of a pebble conglomerate, which marks the Cretaceous unconformity; deposited on a broad, sandy mudflat (Imlay, 1980; Blakey and others, 1983); 250 feet (75 m) thick in Cedar Canyon and 50 to 150 feet (15–45 m) thick in the southeast part of the Panguitch 30´ x 60´ quadrangle (Doelling and Willis, 1999).

Jcp **Paria River Member** (Middle Jurassic, Bathonian) – Consists of three parts not mapped separately: (1) upper part is about 50 feet (15 m) of cliff-forming, olive-gray, micritic and argillaceous limestone and calcareous mudstone; laminated in very thick beds; locally contains small pelecypod fossils; (2) middle part is about 20 feet (6 m) of reddish-brown and greenish-gray shale that forms slope; and (3) lower part is gypsum and minor interbedded shale as much as 80 feet (25 m) thick in nodular, highly fractured and contorted beds and as thin, laminated beds. Upper contact is sharp and planar; deposited in shallow-marine and coastal-sabkha environments (Imlay, 1980; Blakey and others, 1983); Sprinkel and others (2011a) reported an $^{40}Ar/^{39}Ar$ age of 165.9 ± 0.51 Ma on lower Paria River strata in southcentral Utah; 173 feet (53 m) thick in Cedar Canyon and 150 to 400 feet (45–120 m) thick in the southeast part of the Panguitch 30´ x 60´ quadrangle (Doelling and Willis, 1999).

Jcx **Crystal Creek Member** (Middle Jurassic, Bathonian) – Thin- to medium-bedded, reddish-brown siltstone, mudstone, and fine to medium-grained sandstone; commonly gypsiferous and contains local contorted pods of gypsum; forms vegetated, poorly exposed slopes; upper contact is sharp and broadly wavy and corresponds to the base of the thick Paria River gypsum bed; Kowallis and others (2001) reported two $^{40}Ar/^{39}Ar$ ages of 167 to 166 Ma for altered volcanic ash beds within the member near Gunlock that were likely derived from a magmatic arc in what is now southern California and western Nevada; deposited in coastal-sabkha and tidal-flat environments (Imlay, 1980; Blakey and others, 1983); 294 feet (90 m) thick in Cedar Canyon.

Jcc **Co-op Creek Limestone Member** (Middle Jurassic, Bajocian) **–** Thin- to medium-bedded, light-gray micritic limestone and calcareous shale; locally contains *Isocrinus* sp. crinoid columnals, pelecypods, and gastropods; forms sparsely vegetated, ledgy slopes and cliffs; Kowallis and others (2001) reported several $^{40}Ar/^{39}Ar$ ages of 168 to 167 Ma for altered volcanic ash beds within the lower part of the member in southwest Utah that were likely derived from a magmatic arc in what is now southern California and western Nevada; Sprinkel and others (2011a) reported $^{40}Ar/^{39}Ar$ ages of 169.2 ± 0.51 Ma and 169.9 ± 0.49 Ma on two ash beds in the lower part of the member in southwestern Utah; deposited in a shallow-marine environment (Imlay, 1980; Blakey and others, 1983); probably about 400 feet (120 m) thick; the member is as much as about

350 feet (105 m) thick on the Kolob Terrace north of Zion National Park (Biek and Hylland, 2007).

Jcn **Carmel Formation (Co-op Creek Limestone Member), Temple Cap Formation, and Navajo Sandstone, undivided** (Middle to Lower Jurassic) – Poorly exposed in fault blocks near Parowan Gap, where it consists of light-gray micritic limestone and calcareous shale (Co-op Creek Limestone Member of the Carmel Formation), reddish-brown mudstone and siltstone (Temple Cap Formation), and massively cross-bedded, light-gray or white sandstone that consists of well-rounded, fine- to medium-grained, frosted quartz (Navajo Sandstone); incomplete section several tens of feet thick.

Unconformity (J-2?) (Pipiringos and O'Sullivan, 1978), formed about 169 to 168 million years ago in northern Utah, but new radiometric ages and palynomorph data suggest that the J-2 may not exist or is a very short hiatus in southern Utah (Sprinkel and others, 2011a).

Jct **Carmel and Temple Cap Formations, undivided** (Middle to Lower Jurassic, Bajocian to Aalenian) – Poorly exposed in fault blocks near Parowan Gap, where it consists of light-gray micritic limestone and calcareous shale (Co-op Creek Limestone Member of the Carmel Formation) and reddish-brown mudstone and siltstone (Temple Cap Formation); also used to denote the entire Carmel and Temple Cap Formations on cross sections; Sprinkel and others (2011a) reported that the Temple Cap Formation ranges from about 173 to 171 Ma based on several $^{40}Ar/^{39}Ar$ and U-Pb zircon ages; deposited in coastal-sabkha and tidal-flat environments (Blakey, 1994; Peterson, 1994); incomplete section about 30 feet (10 m) thick near Parowan Gap (Maldonado and Williams, 1993a).

Jt **Temple Cap Formation** (Middle to Lower Jurassic) – Not mapped separately; see Biek and others (2009) and Sprinkel and others (2011a) for a description of this formation in southwesternmost Utah.

Unconformity (J-1) (Pipiringos and O'Sullivan, 1978), formed prior to 173 million years ago in southwest Utah (Sprinkel and others, 2011a).

Jn **Navajo Sandstone** (Lower Jurassic) **–** Massively cross-bedded, poorly to moderately well-cemented, light-gray or white sandstone that consists of well-rounded, fine- to medium-grained, frosted quartz sand; upper, unconformable contact is sharp and planar and regionally corresponds to a prominent break in slope, with cliff-forming, cross-bedded sandstone below and reddish-brown mudstone of the Temple Cap Formation above; deposited in a vast coastal and inland dune field with prevailing winds principally from the north (Blakey, 1994, Peterson, 1994); correlative in part with the Nugget Sandstone of northern Utah and Wyoming and the Aztec Sandstone of southern Nevada and adjacent areas (see, for example, Kocurek and Dott, 1983; Riggs and others, 1993; Sprinkel, 2009; Sprinkel and others, 2011b); much of the sand may originally have been transported to areas north and northwest of Utah via a transcontinental river system that tapped Grenvillian-age (about 1.0 to 1.3 Ga) crust involved in Appalachian orogenesis of eastern North America (Dickinson and Gehrels, 2003; Rahl and others, 2003; Reiners and others, 2005); Mohn (1986) measured an incomplete section at Parowan Gap of 1090 feet (332 m); the entire formation is about 1800 to 2300 feet (550–700 m) thick in southwest Utah (Biek and others, 2009).

ACKNOWLEDGMENTS

This geologic map is a compilation modified from 1:24,000-scale geologic maps shown on the index map, combined with original field mapping of the Blind Spring Mountain, Casto Canyon, Flanigan Arch, George Mountain, Haycock Mountain, Henrie Knolls, Panguitch Lake, Red Creek Reservoir, Summit, Tropic Canyon, Tropic Reservoir, Webster Flat, and Wilson Peak 7.5' quadrangles. As the acknowledgments of those individual map authors attest, we are indebted to a great many people for their help over the years. We thank Van Williams, David Nealey, and Ed Sable (all USGS, retired) for sharing their considerable knowledge of this area. We also thank Jim Kirkland (UGS), Eric Roberts (James Cook University, Australia), and Alan Titus (Grand Staircase-Escalante National Monument) for sharing their knowledge of Cretaceous and Tertiary sedimentary strata of southwest Utah. Doug Sprinkel (UGS) and Hellmut Doelling (UGS, retired) provided measured sections of Carmel strata in Cedar Canyon, and Doug also reinterpreted formation tops for many oil and gas exploration wells in the map area. David Dinter (University of Utah) discovered previously unreported structural complications in the Parowan Gap area, which lead author Biek worked to elucidate. Dave Hacker (Kent State University) shared his knowledge of laccolith development and the formation of gravity slide deposits, as well as his preliminary research on the Iron Peak laccolith. We appreciate the help of Terry Spell and Kathleen Zanetti (University of Nevada—Las Vegas) and Bill McIntosh and Lisa Peters (New Mexico Geochronology Research Laboratory) for $^{39}Ar/^{40}Ar$ analyses. Colleagues Grant Willis, Mike Hylland, Robert Ressetar, and Doug Sprinkel (UGS) provided preliminary reviews of the map; we are grateful for their collective wisdom. Finally, we thank Lori Steadman and Jay Hill (UGS) for drafting figures and vectorizing several of the original geologic source maps. This geologic map was funded by the Utah Geological Survey and U.S. Geological Survey, National Cooperative Geologic Mapping Program, through USGS STATEMAP award numbers 08HQAG0096, G09AC00152, G10AC00386, and G11AC20249.

REFERENCES

Agenbroad, L.D., Brunelle, A., and Ort, M., 1996, The Mammoth Summit glacier, Iron County, Utah [abs.]: American Quaternary Association, Program and Abstracts of the 14th Biennial Meeting—Global warming, interglacials, interstadials, climatic optima, and other events, p. 146.

Anderson, J.J., 1965, Geology of the northern Markagunt Plateau, Utah: The University of Texas at Austin, Ph.D. dissertation, 2 plates, scale 1:62,500, 194 p.

Anderson, J.J., 1971, Geology of the southwestern High Plateaus of Utah—Bear Valley Formation, an Oligocene-Miocene volcanic arenite: Geological Society of America Bulletin, v. 82, p. 1179–1206.

Anderson, J.J., 1987, Late Cenozoic drainage history of the northern Markagunt Plateau, Utah, *in* Kopp, K.S., and Cohenour, R.E., editors, Cenozoic geology of western Utah: Utah Geological Association Publication 16, p. 271–278.

Anderson, J.J., 1993, The Markagunt Megabreccia—large Miocene gravity slides mantling the northern Markagunt Plateau, southwestern Utah: Utah Geological Survey Miscellaneous Publication 93-2, 37 p.

Anderson, J.J., 2001, Late Oligocene-early Miocene normal faulting along west-northwest strikes, northern Markagunt Plateau, Utah, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin –a symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists, Utah Geological Association Publication 30, p. 97–111.

Anderson, J.J., and Rowley, P.D., 2002, The Oligocene Isom Formation, Utah and Nevada—a regional ash-flow tuff sheet containing fluidal features of a lava flow [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 4, p. 9.

Anderson, J.J., and Grant, T.C., 1986, Geologic map of the Fremont Pass quadrangle, Iron and Garfield Counties, Utah: Utah Geological and Mineral Survey Map 81, 6 p., 2 plates, scale 1:24,000.

Anderson, J.J., Iivari, T.A., and Rowley, P.D., 1987, Geologic map of the Little Creek Peak quadrangle, Garfield and Iron Counties, Utah: Utah Geological and Mineral Survey Map 104, 11 p., 2 plates, scale 1:24,000.

Anderson, J.J., and Rowley, P.D., 1975, Cenozoic stratigraphy of southwestern high plateaus of Utah, *in* Anderson, J.J., Rowley, P.D., Fleck, R.J., and Nairn, A.E.M., editors, Cenozoic geology of southwestern high plateaus of Utah: Geological Society of America Special Paper 160, p. 1–51.

Anderson, J.J., and Rowley, P.D., 1987, Geologic map of the Panguitch NW quadrangle, Iron and Garfield Counties, Utah: Utah Geological and Mineral Survey Map 103, 8 p., 2 plates, scale 1:24,000.

Anderson, J.J., and Rowley, P.D., 2002, The Oligocene Isom Formation, Utah-Nevada—a regional ash-flow tuff sheet containing fluidal structures of a lava flow [abs.]: Geological Society of America Abstracts with Program, v. 34, no. 5, p. A-9.

Anderson, J.J., Rowley, P.D., Blackman, J.T., Mehnert, H.H., and Grant, T.C., 1990a, Geologic map of the Circleville Canyon area, southern Tushar Mountains and northern Markagunt Plateau, Beaver, Garfield, Iron, and Piute Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2000, scale 1:50,000.

Anderson, J.J., Rowley, P.D., Machette, M.M., Decatur, S.H., and Mehnert, H.H., and 1990b, Geologic map of the Nevershine Hollow area, eastern Black Mountains, southern Tushar Mountains, and northern Markagunt Plateau, Beaver and Iron Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1999, scale 1:50,000.

Anderson, J.J., Thomas, K.M., and Fryman, M.D., 1990c, The welded tuffs of the Isom Formation (Oligocene) of Utah and Nevada—ash-flows, lava flows, or both? [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 2.

Anderson, L.P., and Dinter, D.A., 2010, Deformation and sedimentation in the southern Sevier Foreland, Red Hills, southwestern Utah, *in* Carney, S.M., Tabet, D.E., and Johnson, C.L., editors, Geology of south-central Utah: Utah Geological Association Publication 39, p. 338–366.

Anderson, R.E., and Christenson, G.E., 1989, Quaternary faults, folds, and selected volcanic features in the Cedar City 1° x 2° quadrangle, Utah: Utah Geological and Mineral Survey Miscellaneous Publication 89-6, 29 p., scale 1:250,000.

Anderson, R.S., Hasbargen, J., Koehler, P.A., and Feiler, E.J., 1999, Late Wisconsin and Holocene subalpine forests of the Markagunt Plateau of Utah, southwestern Colorado Plateau, U.S.A.: Arctic, Antarctic, and Alpine Research, v. 31, no. 4, p. 366–378.

Anderson, R.E., and Mehnert, H.H., 1979, Reinterpretation of the history of the Hurricane fault in Utah, *in* Newman, G.W., and Goode, H.D., editors, 1979 Basin and Range Symposium: Rocky Mountain Association of Geologists and Utah Geological Association, p. 145–165.

Andrews, G.D.M., and Branney, M.J., 2005, Folds, fabrics, and kinematic criteria in rheomorphic ignimbrites of the Snake River Plain, Idaho – insights into emplacement and flow, *in* Pederson, J., and Dehler, C.M., editors, Interior Western United States: Geological Society of America Field Guide 6, p. 311–327.

Angelier, J., Colletta, B., and Anderson, R.E., 1985, Neogene paleostress changes in the Basin and Range—a case study at Hoover Dam, Nevada-Arizona: Geological Society of America Bulletin, v. 96, p. 347–361.

Ashland, F.X., 2003, Characteristics, causes, and implications of the 1998 Wasatch Front landslides, Utah: Utah Geological Survey Special Study 105, 49 p.

Averitt, P., 1962, Geology and coal resources of the Cedar Mountain quadrangle, Iron County, Utah: U.S. Geological Survey Professional Paper 389, 71 p., 3 plates, scale 1:24,000.

Averitt, P., and Threet, R.L., 1973, Geologic map of the Cedar City quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-1120, scale 1:24,000.

Baer, J.L., and Steed, R.H., 2010, Geology of Kodachrome Basin State Park, Utah, *in* Sprinkel, D.A., Chidsey, T.C., and Anderson, P.B., editors, Geology of Utah's parks and monuments: Utah Geological Association and Bryce Canyon Natural History Association, Utah Geological Association Publication 28, third edition, p. 467–482.

Bakewell, E.F., 2001, Petrographic analysis of Brian Head chert, *in* Canaday, T.W., High-altitude archaeological investigations at Cedar Breaks National Monument, Utah: National Park Service, Intermountain region, Cultural Resource Selections No. 17, p. 161–167.

Barker, D.S., 1995, Crystallization and alteration of quartz monzonite, Iron Springs mining district, Utah – relation to associated iron deposits: Economic Geology, v. 90, p. 2197–2217.

Best, M.G., and Brimhall, W.H., 1970, Late Cenozoic basalt types in the western Grand Canyon region, *in* Hamblin, W.K., and Best, M.G., editors, The western Grand Canyon district: Utah Geological Society Guidebook to the Geology of Utah, no. 23, p. 57–74.

Best, M.G., and Brimhall, W.H., 1974, Late Cenozoic alkalic basaltic magmas in the western Colorado Plateaus and the Basin and Range transition zone, U.S.A., and their bearing on mantle dynamics: Geological Society of America Bulletin, v. 85, no. 11, p. 1677–1690.

Best, M.G., Christiansen, E.H., and Blank, R.H., Jr., 1989a, Oligocene caldera complex and calc-alkaline tuffs and lavas of the Indian Peak volcanic field, Nevada and Utah: Geological Society of America Bulletin, v. 101, p. 1076–1090.

Best, M.G., Christiansen, E.H., Deino, A.L., Grommé, C.S., McKee, E.H., and Noble, D.C., 1989b, Excursion 3A—Eocene through Miocene volcanism in the Great Basin of the western United States, *in* Chapin, C.E., and Zidek, J., editors, Field excursions to volcanic terranes in the Western United States, Volume II, Cascades and Intermountain West: New Mexico Bureau of Mines and Mineral Resources Memoir 47, p. 91–133.

Best, M.G., and Grant, S.K., 1987, Stratigraphy of the volcanic Oligocene Needles Range Group in southwestern Utah and eastern Nevada: U.S. Geological Survey Professional Paper 1433A, p. 1–28.

Best, M.G., McKee, E.H., and Damon, P.E., 1980, Space-time-composition patterns of late Cenozoic mafic volcanism, southwestern Utah and adjoining areas: American Journal of Science, v. 280, p. 1035–1050.

Best, M.G., Scott, R.B., Rowley, P.D., Swadley, WC, Anderson, R.E., Grommé, C.S., Harding, A.E., Deino, A.L., Christiansen, E.H., Tingey, D.G., and Sullivan, K.R., 1993, Oligocene-Miocene caldera complexes, ash-flow sheets, and tectonism in the central and southeastern Great Basin, *in* Lahren, M.M., Trexler, J.H., Jr., and Spinosa, C., editors, Crustal evolution of the Great Basin and Sierra Nevada: Geological Society of America, Cordilleran-Rocky Mountain Section Guidebook, p. 285–311.

Biek, R.F., 2007, Geologic map of the Kolob Reservoir quadrangle, Washington and Iron Counties, Utah: Utah Geological Survey Map 220, 2 plates, scale 1:24,000.

Biek, R.F., in preparation, Interim geologic map of the Cow Creek quadrangle, Garfield County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., in preparation, Interim geologic map of the Flake Mountain East quadrangle, Garfield County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., in preparation, Interim geologic map of the Flake Mountain West quadrangle, Garfield County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., in preparation, Interim geologic map of the George Mountain quadrangle, Garfield and Kane Counties, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., in preparation, Interim geologic map of the Haycock Mountain quadrangle, Garfield County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., in preparation, Interim geologic map of the Webster Flat quadrangle, Iron County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., and Eaton, J.G., in preparation, Interim geologic map of the Casto Canyon quadrangle, Garfield County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., and Eaton, J.G., in preparation, Interim geologic map of the Tropic Reservoir quadrangle, Garfield County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., and Eaton, J.G., in preparation, Interim geologic map of the Wilson Peak quadrangle, Garfield County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., Eaton, J.G., and Pollock, G.L., in preparation, Interim geologic map of the Tropic Canyon quadrangle, Garfield County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., and Hylland, M.D., 2007, Geologic map of the Cogswell Point quadrangle, Washington, Kane, and Iron Counties, Utah: Utah Geological Survey Map 221, 2 plates, scale 1:24,000.

Biek, R.F., Maldonado, F., and Sable, E.G., in preparation, Interim geologic map of the Summit quadrangle, Iron and Kane Counties, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., Moore, D.W., and Nealey, L.D., 2011, Geologic map of the Henrie Knolls quadrangle, Garfield, Kane, and Iron Counties, Utah: Utah Geological Survey Map 252DM, 2 plates, scale 1:24,000.

Biek, R.F., Rowley, P.D., Hayden, J.M., Hacker, D.B., Willis, G.C., Hintze, L.F., Anderson, R.E., and Brown, K.D., 2009, Geologic map of the St. George and east part of the Clover Mountains 30' x 60' quadrangles, Washington and Iron Counties, Utah: Utah Geological Survey Map 242, 2 plates, 101 p., scale 1:100,000.

Biek, R.F., and Sable, E.G., in preparation, Interim geologic map of the Panguitch Lake quadrangle, Iron and Garfield Counties, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Biek, R.F., Willis, G.C., Hylland, M.D., and Doelling, H.H., 2010, Geology of Zion National Park, Utah, *in* Sprinkel, D.A., Chidsey, T.C., and Anderson, P.B., editors, Geology of Utah's parks and monuments: Utah Geological Association and Bryce Canyon Natural History Association, Utah Geological Association Publication 28, third edition, p. 109–143.

Black, B.D., and Hecker, S., compilers, 1999, Fault number 2533, Parowan Valley faults, in Quaternary fault and fold database of the United States: U.S. Geological Survey Web site, http://earthquakes.usgs.gov/regional/qfaults, accessed 04/26/2010 02:15 PM.

Blakey, R.C., 1994, Paleogeographic and tectonic controls on some Lower and Middle

Jurassic erg deposits, Colorado Plateau, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Colorado, Rocky Mountain Section of the Society for Sedimentary Geology, p. 273–298.

Blakey, R.C., Peterson, F., Caputo, M.V., Geesman, R.C., and Voorhees, B.J., 1983, Paleogeography of Middle Jurassic continental, shoreline, and shallow marine sedimentation, southern Utah, *in* Reynolds, M.W., and Dolley, E.D., editors, Mesozoic paleogeography of west-central United States: Denver, Colorado, Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, p. 77–100.

Blank, H.R., Jr., 1959, Geology of the Bull Valley district, Washington County, Utah: Seattle, University of Washington, Ph.D. dissertation, 177 p.

Blank, H.R., Jr., Butler, W.C., and Saltus, R.W., 1998, Neogene uplift and radial collapse of the Colorado Plateau—regional implications of gravity and aeromagnetic data, *in* Friedman, J.D., and Hoffman, A.C., Jr., coordinators, Laccolith complexes of southeastern Utah—time of emplacement and tectonic setting, Workshop Proceedings: U.S. Geological Survey Bulletin 2158, p. 9–32.

Blank, H.R., and Crowley, J.K., 1990, Geophysical studies, *in* Eppinger, R.G., Winkler, G.R., Cookro, T.M., Shubat, M.A., Blank, H.R., Crowley, J.K., and Jones, J.L., Preliminary assessment of the mineral resources of the Cedar City 1º x 2º quadrangle, Utah: U.S. Geological Survey Open-File Report 90-34, p. 24–42.

Blank, H.R., Jr., and Mackin, J.H., 1967, Geologic interpretation of an aeromagnetic survey of the Iron Springs district, Utah: U.S. Geological Survey Professional Paper 516-B, 14 p.

Blank, H.R., Rowley, P.D. and Hacker, D.B., 1992, Miocene monzonitic intrusions and associated megabreccias of the Iron Axis region, southwestern Utah, *in* Wilson, J.R., editor, Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publication 92-3, p. 399–420.

Bobb, M.C., 1991, The Calico bed, Upper Cretaceous, southern Utah—A fluvial sheet deposit in the Western Interior Foreland Basin and its relationship to Eustasy and tectonics: Boulder, University of Colorado, M.S. Thesis, 166 p.

Bowers, W.E., 1972, The Canaan Peak, Pine Hollow, and Wasatch Formations in the Table Cliff region, Garfield County, Utah: U.S. Geological Survey Bulletin 1331-B, 39 p.

Bowers, W.E., 1973, Geologic map and coal resources of the Pine Lake quadrangle, Garfield County, Utah: U.S. Geological Survey Coal Investigations Map C-66, 2 plates, scale 1:24,000.

Bowers, W.E., 1975, Geologic map and coal resources of the Henrieville quadrangle, Garfield and Kane Counties, Utah: U.S. Geological Survey Coal Investigations Map C-74, 1 plate, scale 1:24,000.

Bowers, W.E., 1990, Geologic map of Bryce Canyon National Park and vicinity, southwestern Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2108, 15 p., 1 plate, scale 1:24,000.

Bown, T.M., Hasiotis, S.T., Maldonado, F., Brouwers, E.M., and Eaton, J.G., 1995, Trace fossils of ants, wasps, and bees (*Hymenoptera*) from the lower Tertiary Claron Formation of southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 27, no. 4, p. 3.

Bown, T.M., Hasiotis, S.T., and Brouwers, E.M., 1995, Reassessment of sedimentary paleoenvironments, late Paleocene to middle Eocene Claron Formation, Paunsaugunt Plateau, southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 27, no. 6, p. A-277.

Bown, T.M., Hasiotis, S.T., Genise, J.F., Maldonado, F., and Bowers, E.M., 1997, Trace fossils of *Hymenoptera* and other insects, and paleoenvironments of the Claron Formation (Paleocene and Eocene), southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range-Colorado Plateau transition zone in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 43–58.

Bullock, K.C., 1970, Iron deposits of Utah: Utah Geological and Mineralogical Survey Bulletin 88, 101 p.

Callaghan, E., 1938, Preliminary report on the alunite deposits of the Marysvale region, Utah: U.S. Geological Survey Bulletin 886-D, p. 91–131.

Canaday, T.W., 2001, High-altitude archaeological investigations at Cedar Breaks National Monument, Utah, with contributions by Bakewell, E.F., Chengyu W., Corson, P.L., Ferris, D.E., Elias, S.A., Funkhouser, G.S., Hughes, R.E., Jackson, S.T., Madsen, D.B., Perry, L., Sarna-Wojciki, A., and Thompson, R.S.: National Park Service, Intermountain region, Cultural Resource Selections No. 17, 203 p.

Cashion, W.B., 1961, Geology and fuels resources of the Orderville-Glendale area, Kane County, Utah: U.S. Geological Survey Coal Investigations Map C-49, scale 1:62,500.

Christiansen, R.L., and Lipman, P.W., 1972, Cenozoic volcanism and plate tectonic evolution of the western United States—II. Late Cenozoic: Royal Society of London Philosophical Transactions (A), v. 271, p. 249–284.

Cifelli, R.L., Kirkland, J.I., Weil, A., Deinos, A.R., and Kowallis, B.J., 1997, High-precision $^{40}Ar/^{39}Ar$ geochronology and the advent of North America's Late Cretaceous terrestrial fauna: Proceedings National Academy of Science USA, v. 94, p. 11163–11167.

Cook, E.F., 1960, Geologic atlas of Utah, Washington County: Utah Geological and Mineralogical Survey Bulletin 70, 119 p., scale 1:125,000.

Cook, K.L., and Hardman, E., 1967, Regional gravity survey of the Hurricane fault area and Iron Springs district, Utah: Geological Society of America Bulletin, v. 78, p. 1063–1076.

Cornell, D., Butler, T., Holm, D., Hacker, D., and Spell, T., 2001, Stratigraphy and Ar/Ar ages of volcanic rocks of the Pinto quadrangle, Colorado Plateau transition zone, SW Utah [abs.], *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin—A symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists: Utah Geological Association Publication 30, p. 420–421.

Crawford, A.L., 1951, Diatomaceous earth near Bryce Canyon National Park, Utah: Utah Geological and Mineralogical Survey Circular 38, 34 p.

Cunningham, C.G., Rowley, P.D., Steven, T.A., and 2007, Geologic evolution and mineral resources of the Marysvale volcanic field, west-central Utah, *in* Willis, G.C., Hylland, M.D., Clark, D.L., and Chidsey, T.C., Jr., editors, Central Utah—diverse geology of a dynamic landscape: Utah Geological Association Publication 36, p. 143–161.

Cunningham, C.G., Rye, R.O., Rockwell, B.W., Kunk, M.J., and Councell, T.B., 2005, Supergene destruction of a hydrothermal replacement alunite deposit at Big Rock Candy Mountain, Utah—mineralology, spectroscopic remote sensing, stable-isotope, and argon-age evidences: Chemical Geology, v. 215, p. 317–337.

Currey, D.R., Mulvey, W.E., and Lindsay, L.M.W., 1986, Markagunt Plateau, Utah – southern margin of late Wisconsinan montane glaciation in the great Basin [abs.]: American Quaternary Association Program and Abstracts, v. 35, no 9, p. 126.

Dalrymple, G.B., 1979, Critical tables for conversion of K-Ar ages from old to new constants: Geology, v. 7, p. 558–560.

Damon, P.E., 1968, Correlation and chronology of ore deposits and volcanic rocks: Tucson, University of Arizona Geochronology Lab, Annual Program Report C00-689-100, U.S. Atomic Energy Commission contract AT(11-1) – 689, 75 p.

Davis, G.H., 1990, Shortening of the Claron Formation at Bryce Canyon, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 17.

Davis, G.H., 1991, The structural geology of Bryce Canyon hoodoos [abs.]: Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 20.

Davis, G.H., 1997a, Field guide to geologic structures in the Zion-Bryce-Cedar Breaks region, Utah: Geological Society of America Penrose Conference on Tectonics of Continental Interiors, 127 p.

Davis, G.H., 1997b, Field guide to geologic structures in the Bryce Canyon region, Utah: American Association of Petroleum Geologists Hedberg Research Conference on Reservoir-scale Deformation—characterization and prediction, 119 p.

Davis, G.H., 1999, Structural geology of the Colorado Plateau region of southern Utah, with special emphasis on deformation bands: Geological Society of America Special Paper 342, 157 p.

Davis, G.H., and Krantz, R.W., 1986, Post-Laramide thrust faults in the Claron Formation, Bryce Canyon National Park, Utah [abs.]: Geological Society of America Abstracts with programs, v. 18, p. 98.

Davis, G.H., and Pollock, G.L., 2010, Geology of Bryce Canyon National Park, *in* Sprinkel, D.A., Chidesy, T.C., Jr., and Anderson, P.B., editors, Geology of Utah's parks and monuments, third edition, p. 37–60.

Davis, G.H., and Rowley, P.D., 1993, Miocene thrusting, gravity sliding, and near-surface batholithic emplacement, Marysvale volcanic field, southwestern Utah [abs.]: Eos (Transactions, American Geophysical Union), v. 74, no. 43, p. 647.

Davis, S.J., Mulch, A., Carroll, A.R., Horton, T.W., and Chamberlain, C.P., 2009, Paleogene landscape evolution of the central North American Cordillera—developing topography and hydrology in the Laramide foreland: Geological Society of America Bulletin, v. 121, no. 1/2, p. 100–116.

Dickinson, W.R., and Gehrels, G.E., 2003, U-Pb ages of detrital zircons from Permian and Jurassic eolian sandstones of the Colorado Plateau, USA—paleogeographic implications: Sedimentary Geology, v. 163, issues 1–2, p. 29–66.

Dickinson, W.R., and Gehrels, G.E., 2009a, U-Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau—evidence for transcontinental dispersal and intraregional recycling of sediment: Geological

Society of America Bulletin, v. 121, nos. 3 and 4, p. 408–433.

Dickinson, W.R., and Gehrels, G.E., 2009b, Insights into North American paleogeography and paleotectonics from U-Pb ages of detrital zircons in Mesozoic strata of the Colorado Plateau USA: International Journal Earth Science, DOI 10.1007/s00531-009-0462-0, 19 p.

Dickinson, W.R., Stair, K.N., Gehrels, G.E., Peters, L., Kowallis, B.J., Blakey, R.C., Amar, J.R., and Greenhalgh, B.W., 2009, U-Pb and $^{40}Ar/^{39}Ar$ ages for a tephra lens in the Middle Jurassic Page Sandstone—first direct isotopic dating of a Mesozoic eolianite on the Colorado Plateau: The Journal of Geology, v. 118, p. 215–221.

Doelling, H.H., 2008, Geologic map of the Kanab 30' x 60' quadrangle, Kane and Washington Counties, Utah, and Coconino and Mohave Counties, Arizona: Utah Geological Survey Miscellaneous Publication MP-08-2DM, scale 1:100,000.

Doelling, H.H., and Davis, F.D., 1989, The geology of Kane County, Utah—geology, mineral resources, geologic hazards: Utah Geological and Mineral Survey Bulletin 124, 192 p., 10 plates, scale 1:100,000.

Doelling, H.H., and Graham, R.L., 1972, Southwestern Utah coal fields—Alton, Kaiparowits Plateau, and Kolob-Harmony: Utah Geological and Mineral Survey Monograph Series 1, 333 p.

Doelling, H.H., and Kuehne, P., in press, Geologic map of the Short Canyon quadrangle, Emery County, Utah: Utah Geological Survey Map 255DM, scale 1:24,000.

Doelling, H.H., and Willis, G.C., 1999a, Interim geologic map of the SE part of the Panguitch 30' x 60' quadrangle, Garfield and Kane Counties, Utah: Utah Geological Survey Open-File Report 367, 10 p., 1 plate, scale 1:100,000.

Doelling, H.H., and Willis, G.C., 1999b, Interim geologic map of the Escalante and parts of the Loa and Hite Crossing 30' x 60' quadrangles, Garfield and Kane Counties, Utah: Utah Geological Survey Open-File Report 368, 24 p., 1 plate, scale 1:100,000.

Doelling, H.H., and Willis, G.C., 2006, Geologic map of the Smoky Mountain 30' x 60' quadrangle, Kane and San Juan Counties, Utah and Coconino County, Arizona: Utah Geological Survey Map 213, 2 plates, scale 1:100,000.

Downing, R.F., 2000, Imaging the mantle in southwestern Utah using geochemistry and geographic information systems: Las Vegas, University of Nevada, M.S. thesis, 128 p.

DuRoss, C.B., and Kirby, S.M., 2004, Reconnaissance investigation of ground cracks along the western margin of Parowan Valley, Iron County, Utah: Utah Geological Survey Report of Investigation 253, 17 p.

Dyman, T.S., Cobban, W.A., Titus, A., Obradovich, J.D., Davis, L.E., Eves, R.L., Pollock, G.L., Takahashi, K.I., and Hester, T.C., 2002, New biostratigraphic and radiometric ages for Albian-Turonian Dakota Formation and Tropic Shale at Grand Staircase-Escalante National Monument and Iron Springs Formation near Cedar City, Parowan, and Gunlock, Utah: Geological Society of America Abstracts with Programs, v. 34, no. 4, p. A-13.

Eaton, J.G., 1991, Biostratigraphic framework for the Upper Cretaceous rocks of the Kaiparowits Plateau, southern Utah, *in* Nations, J.D., and Eaton, J.G., editors, Stratigraphy, depositional environments, and sedimentary tectonics of the western margin, Cretaceous Western Interior Seaway: Geological Society of America Special Paper 260, p. 47–63.

Eaton, J.G., 1993, Composition and stratigraphic interpretation of Cretaceous strata of the Paunsaugunt Plateau, Utah, *in* Morales, M., editor, Aspects of Mesozoic geology and paleontology of the Colorado Plateau, p. 153–161.

Eaton, J.G., 1999, Vertebrate paleontology of the Iron Springs Formation, Upper Cretaceous, southwestern Utah, *in* Gillette, D.D., editor, Vertebrate paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 339–343.

Eaton, J.G., 2006, Late Cretaceous mammals from Cedar Canyon, southwestern Utah, *in* Lucas, S.G., and Sullivan, R.M., editors, Late Cretaceous vertebrates from the Western Interior: New Mexico Museum of Natural History and Science Bulletin 35, p. 373–402.

Eaton, J.G., 2009, Cenomanian (Late Cretaceous) Mammals from Cedar Canyon, southwestern Utah, and a revision of Cenomanian *Alphadon*-like marsupials, *in* Albright, L. B., III, editor, Papers on Geology, Paleontology, and Biostratigraphy in Honor of Michael O. Woodburne: Museum of Northern Arizona Bulletin, v. 65, p. 97–110.

Eaton, J.G., Tibert, N.E., and Biek, R.F., 2011, First mammals and ostracodes from the Paleogene Claron Formation, southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 4, p. 77.

Eaton, J.G., Diem, S., Archibald, J.D., Schierup, C., and Munk, H., 1999a, Vertebrate paleontology of the Upper Cretaceous rocks of the Markagunt Plateau, southwestern Utah, *in* Gillette, D.D., editor, Vertebrate paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 323–333.

Eaton, J.G., Hutchinson, J.H., Holroyd, P.A., Korth, W.W., and Goldstrand, P.M., 1999c, Vertebrates of the turtle basin local fauna, middle Eocene, Sevier Plateau, south-central Utah, *in* Gillette, D.D., editor, Vertebrate paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 463–468.

Eaton, J.G., Kirkland, J.I., Hutchinson, J.H., Denton, R., O'Neill, R.C., and Parrish, J.M., 1997, Nonmarine extinction across the Cenomanian-Turonian boundary, southwestern Utah, with a comparison to the Cretaceous-Tertiary extinction event: Geological Society of America Bulletin, v. 109, p. 560–567.

Eaton, J.G., Maldonado, F., and McIntosh, W.C., 1999b, New radiometric dates from Upper Cretaceous rocks of the Markagunt Plateau, southwestern Utah, and their bearing on subsidence histories [abs.]: Geological Society of America Abstracts with Programs, v. 31, no. 4, p. A-11.

Eaton, J.G., Laurin, J., Kirkland, J.I., Tibert, N.E., Leckie, R.M., Sageman, B.B., Goldstrand, P.M., Moore, D.W., Straub, A.W., Cobban, W.A., and Dalebout, J.D., 2001, Cretaceous and early Tertiary geology of Cedar and Parowan Canyons, western Markagunt Plateau, Utah, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin – a symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists, Utah Geological Association Publication 30, p. 337–363.

Feist, M., Eaton, J.G., Brouwers, E.M., and Maldonado, F., 1997, Significance of Charophytes from the lower Tertiary variegated and volcaniclastic units, Brian Head Formation, Casto Canyon area, southern Sevier Plateau, southwestern Utah, *in*, Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range—Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 27–42.

Fillmore, R.P., 1991, Tectonic influence on sedimentation in the southern Sevier foreland, Iron Springs Formation (Upper Cretaceous), southwestern Utah, *in* Nations, J.D., and Eaton, J.G., editors, Stratigraphy, depositional environments, and sedimentary tectonics of the western margin, Cretaceous Western Interior Seaway: Geological Society of America Special Paper 260, p. 9–25.

Fleck, R.J., Anderson, J.J., and Rowley, P.D., 1975, Chronology of mid-Tertiary volcanism in High Plateaus region of Utah, *in* Anderson, J.J., Rowley, P.D., Fleck, R.J., and Nairn, A.E.M., editors, Cenozoic geology of southwestern High Plateaus of Utah: Geological Society of America Special Paper 160, p. 53–61.

Fritton, J.G., James, D., and Leeman, W.P., 1991, Basic magmatism associated with late Cenozoic extension in the western United States – compositional variations in space and time: Journal of Geophysical Research, v. 96, no. B8, p. 13,363–13,711.

Fryman, M.D., 1986, Primary structures of the Baldhills Tuff Member of the Isom Formation, an Oligocene tufflava, southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 18, no. 4, p. 289.

Fryman, M.D., 1987, The Isom Formation on the Markagunt Plateau in southwestern Utah: Kent, Ohio, Kent State University, M.S. thesis, 86 p.

Geissman, J.W., Holm, D., Harlan, S.S., and Embree, G.F., 2010, Rapid, high-temperature formation of large-scale rheomorphic structures in the 2.06 Ma Huckleberry Ridge Tuff, Idaho, USA: Geology, v. 38, p. 263–266.

Giraud, R.E., and Lund, W.R., 2006, The June 3, 2005, Black Mountain debris flow, Iron County, Utah: Utah Geological Survey Technical Report 06-05, 18 p.

Golder, K.B., and Wizevich, M.C., 2009, Wetland trace fossils in the Paleogene Brian Head Formation, southwest Utah [abs.]: Geological Society of America Abstracts with Programs, v. 41, no. 3, p. 88.

Golder, K.B., Wizevich, M.C., Simpson, E.L., and Storm, L.P., 2009, Oligocene ichnofossils in non-marine limestone of the Brian Head Formation, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 262.

Goldstrand, P.M., 1990, Stratigraphy and paleogeography of Late Cretaceous and Early Tertiary rocks of southwest Utah: Utah Geological Survey Miscellaneous Publication 90-2, 58 p.

Goldstrand, P.M., 1991, Tectonostratigraphy, petrology, and paleogeography of the Upper Cretaceous to Eocene rocks of southwest Utah: Reno, University of Nevada, Ph.D. dissertation, 205 p.

Goldstrand, P.M., 1992, Evolution of Late Cretaceous and early Tertiary basins of southwest Utah based on clastic petrology: Journal of Sedimentary Petrology, v. 62, no. 3, p. 495–507.

Goldstrand, P.M., 1994, Tectonic development of Upper Cretaceous to Eocene strata of southwestern Utah: Geological Society of America Bulletin, v. 106, p. 145–154.

Goldstrand, P.M., and Mullett, D.J., 1997, The Paleocene Grand Castle Formation—a new formation on the Markagunt Plateau of southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range-Colorado Plateau transition zone in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 59–78.

Gosse, J.C., Klein, J., Evenson, E.B., Lawn, B., and Middleton, R., 1995, Beryllium-10 dating of the duration and retreat of the last Pinedale glacial sequence: Science, v. 268, p. 1329–1333.

Gosse, J.C., and Phillips, F.M., 2001, Terrestrial *in situ* cosmogenic nuclides—theory and application: Quaternary Science Reviews, v. 20, p. 1475–1560.

Grant, T.C., 1979, Geology of the Spry intrusion, Garfield County, Utah: Kent, Ohio, Kent State University, M.S. thesis, 1 plate, scale 1:24,000, 59 p.

Gregory, H.E., 1950, Geology of eastern Iron County, Utah: Utah Geological and Mineralogical Survey Bulletin 37, 153 p., 1 plate, scale 1:63,360.

Gregory, H.E., 1951, The geology and geography of the Paunsaugunt region: U.S. Geological Survey Professional Paper 226, 116 p., 4 plates, scale 1:62,500.

Gustason, E.R., 1989, Stratigraphy and sedimentology of the middle Cretaceous (Albian-Cenomanian) Dakota Formation, southwestern Utah: Boulder, University of Colorado, Ph.D. dissertation, 376 p.

Hacker, D.B., 1998, Catastrophic gravity sliding and volcanism associated with the growth of laccoliths—examples from early Miocene hypabyssal intrusions of the Iron Axis magmatic province, Pine Valley Mountains, southwestern Utah: Kent, Ohio, Kent State University, Ph.D. dissertation, 5 plates, 258 p.

Hacker, D.B., Holm, D.K., Rowley, P.D., and Blank, H.R., 2002, Associated Miocene laccoliths, gravity slides, and volcanic rocks, Pine Valley Mountains and Iron Axis region, southwestern Utah, *in* Lund, W.R., editor, Field guide to geologic excursions in southwestern Utah and adjacent areas of Arizona and Nevada: U.S. Geological Survey Open-File Report OF 02-0172, p. 235–283.

Hacker, D.B., Petronis, M.S., Holm, D.K., and Geissman, J.W., 2007, Shallow emplacement mechanisms of the Miocene Iron Axis laccolith group, southwest Utah, *in* Lund, W.R., editor, Field guide to geologic excursions in southern Utah: Utah Geological Association Publication 35, 49 p., compact disk.

Hacker, D.B., Rowley, P.D., Blank, H.R., and Snee, L.W., 1996, Deformational structures related to the emplacement and growth of the Pine Valley laccolith, southern Iron Axis region, Washington County, Utah [abs.]: Eos Transactions, American Geophysical Union, v. 76, no. 46, p. 625.

Hamblin, W.K., 1963, Late Cenozoic basalts of the St. George basin, Utah, *in* Heylmun, E.B., editor, Guidebook to the geology of southwestern Utah—Transition between the Basin-Range and Colorado Plateau provinces: Salt Lake City, Intermountain Association of Petroleum Geologists 12th Annual Field Conference, p. 84–89.

Hamblin, W.K., 1970, Late Cenozoic basalt flows of the western Grand Canyon, *in* Hamblin, W.K., and Best, M.G., editors, The western Grand Canyon district: Utah Geological Society Guidebook to the Geology of Utah, no. 23, p. 21–38.

Hamblin, W.K., 1987, Late Cenozoic volcanism in the St. George basin, Utah, *in* Beus, S.S., editor, Geological Society of America Centennial Field Guide—Volume 2, Rocky Mountain Section: Geological Society of America, p. 291–294.

Hamblin, W.K., Damon, P.E., and Bull, W.B., 1981, Estimates of vertical crustal strain rates along the western margins of the Colorado Plateau: Geology, v. 9, p. 293–298.

Hasiotis, S.T., and Bown, T.M., 1997, Crayfish (*Decapoda, Cambaridae*) burrows and their paleohydrologic and paleoenvironmental significance, Paleocene-Eocene Claron Formation, Markagunt Plateau, southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 29, no. 2, p. 13.

Hatfield, S.C., Rowley, P.D., Sable, E.D., Maxwell, D.J., Cox, B.V., McKell, M.D., and Kiel, D.E., 2004, Geologic road log of Cedar Breaks National Monument, Utah, *in* Anderson, P.B., and Sprinkel, D.A., editors, Geologic road, trail, and lake guides to Utah's parks and monuments: Utah Geological Association Publication 29, Second Edition, p. 1–9, on CD.

Hatfield, S.C., Rowley, P.D., Sable, E.D., Maxwell, D.J., Cox, B.V., McKell, M.D., and Kiel, D.E., 2010, Geology of Cedar Breaks National Monument, Utah, *in* Sprinkel, D.A., Chidsey, T.C., Jr., and Anderson, P.B., editors, Geology of Utah's parks and monuments: Utah Geological Association and Bryce Canyon Natural History Association, Utah Geological Association Publication 28, Third Edition, p. 145–160.

Heller, P.L., and Paola, C., 1989, The paradox of Lower Cretaceous gravels and the initiation of thrusting in the Sevier orogenic belt, United States Western Interior: Geological Society of America Bulletin, v. 101, p. 864–875.

Hereford, R., 1988, Interim geologic map of the Cannonville quadrangle, Kane and Garfield Counties, Utah: Utah Geological Survey Open-File Report 142, 17 p., 1 plate, scale 1:24,000.

Hunt, G.J., Biek, R.F., DeBlieux, D.D., Madsen, S.K., Milner, A.R.C., Roberts, E.M., and Eaton, J.G., 2011, Dinosaur tracks confirm Late Cretaceous age for the lower Grand Castle Formation, Iron County Utah—stratigraphic and tectonic implications [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 4, p. 16.

Hunt, G.J., Lawton, T.F., and Kirkland, J.I., 2011, Detrital zircon U-Pb geochronological provenance of Lower Cretaceous strata, foreland basin, Utah, *in* Sprinkel, D.A., Yonkee, W.A., and Chidsey. T.C., Jr., editors, Sevier thrust belt—northern and central Utah and adjacent areas: Utah Geological Association Publication 40, p. 193–211.

Hurlow, H.A., 2002, The geology of Cedar Valley, Iron County, Utah, and its relation to ground-water conditions: Utah Geological Survey Special Study 103, 74 p., 2 plates.

Hylland, M.D., 2010, Geologic map of the Clear Creek Mountain quadrangle, Kane County, Utah: Utah Geological Survey Map 245, 2 plates, scale 1:24,000.

Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L., and Shackleton, N.J., 1984, The orbital theory of Pleistocene climate—support from a revised chronology of the marine ^{18}O record, *in* Berger, A., Imbrie, J., Hays. J., Kukla, G., and Saltzman, B., editors, Milankovitch and climate part 1: Dordrecht, Holland, Reidel, p. 269–306.

Imlay, R.W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U.S. Geological Survey Professional Paper 1062, 134 p.

Ipson, D., and Ipson, K., 2008, Remembering Panguitch Lake: Provo, Brigham Young University Print Services, 109 p.

Jinnah, Z.A., and Roberts, E.M., 2011, Facies associations, paleoenvironment, and base-level changes in the Upper Cretaceous Wahweap Formation, Utah, U.S.A.: Journal of Sedimentary Research, v. 81, p. 266–283.

Jinnah, Z.A., Roberts, E.M., Deino, A.L., Larsen, J.S., Link, P.K., and Fanning, C.M., 2009, New $^{40}Ar/^{39}Ar$ and detrital zircon U-Pb ages for the Upper Cretaceous Wahweap and Kaiparowits Formations on the Kaiparowits Plateau, Utah—implications for regional correlation, provenance, and biostratigraphy: Cretaceous Research, v. 30, p. 287–299.

Johnson, B.T., 1984, Depositional environments of the Iron Springs Formation, Gunlock, Utah: Brigham Young University Geology Studies, v. 31, pt. 1, p. 29–46.

Johnson, H.D., Krevitsky, R.D., Link, P.K., and Biek, R.F., 2011, Detrital zircon from the Late Cretaceous middle member Grand Castle Formation, south-central Utah—recycled Mesozoic aeolianites [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 4, p. 68.

Johnson, R.L., Smith, E.I., and Biek, R.F., 2010, Subalkaline volcanism in the Black Rock Desert and Markagunt Plateau volcanic fields of south-central Utah, *in* Carney, S.M., Tabet, D.E., and Johnson, C.L., editors, Geology and geologic resources of south-central Utah: Utah Geological Association Guidebook 39, p. 109–150.

Kauffman, E.G., 1984, Paleobiogeography and evolutionary response dynamic in the Cretaceous western interior seaway of North America: Geological Association of Canada Special Paper 27, p. 273–306.

Kaufman, K.L., and Anderson, J.J., 1981, Ash-flow tuff vent in three dimensions, Markagunt Plateau, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 13, no. 7, p. 483.

Kirkland, J.I., Britt, B., Burge, D.L., Carpenter, K., Cifelli, R., Decourten, F., Eaton, J., Hasiotis, S., and Lawton, T., 1997, Lower to middle Cretaceous dinosaur faunas of the central Colorado Plateau—a key to understanding 35 million years of tectonics, sedimentology, evolution and biogeography, *in* Link, P.K., and Kowallis, B.J., editors, Mesozoic to recent geology of Utah: Brigham Young University Geology Studies, v. 42, part 2, p. 69–103.

Kirkland, J.I., and Madsen, S.K., 2007, The Lower Cretaceous Cedar Mountain Formation, eastern Utah—the view up an always interesting learning curve, *in* Lund, W.R., editor, Field guide to geological excursions in southern Utah: Utah Geological Association Publication 35, p. 1–108, on CD.

Knudsen, T.R., in preparation, Interim geologic map of the Cedar City quadrangle, Iron County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Knudsen, T.R., in preparation, Interim geologic map of the Enoch quadrangle, Iron County, Utah: Utah Geological Survey Open-File Report, scale 1:24,000.

Kocurek, G., and Dott, R.H., Jr., 1983, Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountains region, *in* Reynolds, M.W., and Dolley, E.D., editors, Mesozoic paleogeography of the west-central United States: Denver, Rocky Mountain Section Society of Economic Paleontologists and Mineralogists, p. 101-116.

Korth, W.W., and Eaton, J.G., 2004, Rodents and a marsupial (*Mammalia*) from the Duschesnean (Eocene) of the Sevier Plateau, Utah, *in* Dawson, M.R., and Lillegraven, J.A., editors, Fanfare for an uncommon paleontologist—papers on vertebrate evolution in honor of Malcolm C. McKenna: Carnegie Museum of Natural History Bulletin, no. 36, p. 109–119.

Kowallis, B.J., Sprinkel, D.A., Doelling, H.H., and Kuehne, P.A., 2011, New isotopic ages from the Early and Middle Jurassic of Utah—resolving the age of the Gypsum Spring and Temple Cap Formations [abs.]: Geological Sociiety of America Abstracts with Programs, v. 43, no. 4, p. 1.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Zhang, C., and Everitt, B.H., 2001, The record of Middle Jurassic volcanism in the Carmel and Temple Cap Formations of southwestern Utah: Geological Society of America Bulletin, v. 113, no. 3, p. 373–387.

Kurlich, R.A., III, 1990, Geology of the Hatch 7.5 minute quadrangle, Garfield County, southwestern Utah: Kent, Ohio, Kent State University, M.S. thesis, 104 p., 2 plates, scale 1:24,000.

Kurlich, R.A., III, and Anderson, J.J., 1997, Geologic map of the Hatch quadrangle, Garfield County, Utah: Utah Geological Survey Miscellaneous Publication 97-5, 17 p., 2 plates, scale 1:24,000.

Laabs, B.J.C., and Carson, E.C., 2005, Glacial geology of the southern Uinta Mountains, *in* Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain geology: Utah Geological Association Publication 33, p. 235–253.

Laurin, J., and Sageman, B.B., 2001, Cenomanian-Turonian coastal record in SW Utah, U.S.A.—orbital-scale transgressive-regressive events during oceanic anoxic event II: Journal of Sedimentary Research, v. 77, p. 731–756.

Lawton, T.F., Pollock, S.L., and Robinson, R.A.J., 2003, Integrating sandstone petrology and nonmarine sequence stratigraphy—application to the Late Cretaceous fluvial systems of southwestern Utah, U.S.A.: Journal of Sedimentary Research, v. 73, no. 3, p. 389–406.

Leavitt, R.E., May, S.B., and MacLean, J.S., 2011, Preliminary field investigation into the relationship between hoodoo formation and footwall shearing of the Ruby's Inn thrust fault, Bryce Canyon, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 5, p. 296.

LeBas, M.J., LeMaitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745–750.

Leeman, W.P., 1974, Late Cenozoic alkali-rich basalt from the western Grand Canyon area, Utah and Arizona—isotopic composition of strontium: Geological Society of America Bulletin, v. 85, p. 1691–1696.

Leith, C.K., and Harder, E.C., 1908, The Iron Springs district, southern Utah: U.S. Geological Survey Bulletin 316-E, p. 359–375.

Link, P.K., Roberts, E., Fanning, C.M., and Larsen, J.S., 2007, Detrital-zircon age populations from Upper Cretaceous and Paleogene Wahweap, Kaiparowits, Canaan Peak, Pine Hollow, and Claron Formations, Kaiparowits Plateau, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 39, no. 5, p. 7.

Lipman, P.W., Prostka, H.J., and Christiansen, R.L., 1972, Cenozoic volcanism and plate-tectonic evolution of the Western United States – I. Early and middle Cenozoic: Philosophical Transactions of the Royal Society of London, v. A271, p. 217–248.

Lowder, G.G., 1973, Late Cenozoic transitional alkali olivine-thoeleiitic basalt and andesite from the margin of the Great Basin, southwest Utah: Geological Society of America Bulletin, v. 84, p. 2293–3012.

Lund, W.R., Hozik, M.J., and Hatfield, S.C., 2007, Paleoseismic investigation and long-term slip history of the Hurricane fault in southwestern Utah: Utah Geological Survey Special Study 119, Paleoseismology of Utah, volume 14, 81 p., compact disk.

Lund, W.R., Knudsen, T.R., and Vice, G.S., 2008, Paleoseismic reconnaissance of the Sevier fault, Kane and Garfield Counties, Utah: Utah Geological Survey Special Study 122, Paleoseismology of Utah, volume 16, 31 p.

Lund, W.R., Knudsen, T.R., and Brown, K.E., 2009, Large rock fall closes highway near Cedar City, Utah: Utah Geological Survey, Survey Notes, v. 41, no. 3, p. 8–9.

Lundin, E.R., 1987, Thrusting of the Claron Formation, the Bryce Canyon region, Utah: Tucson, The University of Arizona, M.S. thesis, 51 p.

Lundin, E.R., 1989, Thrusting of the Claron Formation, the Bryce Canyon region, Utah: Geological Society of America Bulletin, v. 101, p. 1038–1050.

Lundin, E.R., and Davis, G.H., 1987, South-southeast vergent thrust faulting and folding of the Eocene(?) Claron Formation, Bryce Canyon National Park region, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 5, p. 317.

Mackin, J.H., 1947, Some structural features of the intrusions in the Iron Springs district: Utah Geological Society Guidebook 2, 62 p.

Mackin, J.H., 1954, Geology and iron deposits of the Granite Mountain area, Iron County, Utah: U.S. Geological Survey Mineral Investigations Field Studies Map MF-14, scale 1:12,000.

Mackin, J.H., 1960, Structural significance of Tertiary volcanic rocks in southwestern Utah: American Journal of Science, v. 258, no. 2, p. 81–131.

Mackin, J.H., 1968, Iron ore deposits of the Iron Springs district, southwestern Utah, *in* Ridge, J.D., editor, Ore deposits of the United States, 1933–1967 (Graton-Sales volume): New York, American Institute of Mining and Metallurgical Petroleum Engineers, v. 2, p. 992–1019.

Mackin, J.H., and Rowley, P.D., 1976, Geologic map of The Three Peaks quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-1297, scale 1:24,000.

Mackin, J.H., Nelson, W.H., and Rowley, P.D., 1976, Geologic map of the Cedar City NW quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-1295, scale 1:24,000.

Madsen, D.B., Sarna-Wojcicki, A.M., and Thompson, R.S., 2002, A late Pleistocene tephra layer in the southern Great Basin and Colorado Plateau derived from Mono Craters, California: Quaternary Research, v. 57, p. 382–390.

Maldonado, F., 1995, Decoupling of mid-Tertiary rocks, Red Hills-western Markagunt Plateau, southwestern Utah, *in* Scott, R.B., and Swadley, W C, editors, Geologic studies in the Basin and Range-Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1992: U.S. Geological Survey Bulletin 2056, p. 233–254.

Maldonado, F., Anderson, J.J., and Biek, R.F., 2011, Preliminary geologic map of the Cottonwood Mountain quadrangle, Iron County, Utah: U.S. Geological Survey Open-File Report 2010-1334, 1 plate, scale 1:24,000.

Maldonado, F., and Moore, R.C., 1995, Geologic map of the Parowan quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map 1762, 1 plate, scale 1:24,000.

Maldonado, F., Sable, E.G., and Anderson, J.J., 1989, Evidence for shallow detachment faulting of mid-Tertiary rocks, Red Hills (Basin and Range) with implications for a more extensive detachment zone in the adjacent Markagunt Plateau, Colorado Plateau, southwest Utah [abs.]: Eos, v. 70, no. 43, p. 1336.

Maldonado, F., Sable, E.G., and Anderson, J.J., 1992, Evidence for a Tertiary low-angle shear zone with implications for a regional zone in the adjacent Colorado Plateau, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 315–323.

Maldonado, F., Sable, E.G., and Nealey, D.L., 1997, Cenozoic low-angle faults, thrust faults, and anatomosing high-angle faults, western Markagunt Plateau, southwesten Utah, *in* Maldonado, F. and Nealey, L.D., editors, Geologic studies in the Basin and Range-Colorado Plateau transition zone in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 151–176.

Maldonado, F., and Williams, V.S., 1993a, Geologic map of the Parowan Gap quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map 1712, 1 plate, scale 1:24,000.

Maldonado, F., and Williams, V.S., 1993b, Geologic map of the Paragonah quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map 1713, 1 plate, scale 1:24,000.

Marchetti, D.W., Cerling, T.E., Dohrenwend, J.C., and Gallin, W., 2007, Ages and significance of glacial and mass movement deposits on the west side of Boulder Mountain, Utah, USA: Palaeogeography, Palaeoclimatology, and Palaeoecology, v. 252, p. 503–513.

Marchetti, D.W., Cerling, T.E., and Lips, E.W., 2005, A glacial chronology for the Fish Creek drainage of Boulder Mountain, Utah, USA: Quaternary Research, v. 64, p. 263–271.

Marchetti, D.W., Harris, M.S., Bailey, C.M., Cerling, T.E., and Bergman, S., 2011, Timing of glaciation and last glacial maximum paleoclimate estimates from the Fish Lake Plateau, Utah: Quaternary Research, v. 75, p. 183–195.

May, S.B., Leavitt, R.E., and MacLean, J.S., 2011, Extent of footwall shear adjacent to the Ruby's Inn thrust fault, southern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 5, p. 116.

McGookey, D.P., 1972, Cretaceous System, *in* Geologic Atlas of the Rocky Mountain Region: Rocky Mountain Association of Geologists, Denver, CO, p. 190–228.

Merle, O.R., Davis, G.H., Nickelsen, R.P., and Gourlay, P.A., 1993, Relation of thin-skinned thrusting of Colorado Plateau strata in southwestern Utah to Cenozoic magmatism: Geological Society of America Bulletin, v. 105, p. 387–398.

Milner, A.R.C., Vice, G.S., Harris, J.D., and Lockley, M.G., 2006, Dinsoaur tracks from the Upper Cretaceous Iron Springs Formation, Iron County, Utah, *in* Lucas, S.G., and Sullivan, R.M., editors, Late Cretaceous vertebrates from the Western Interior: New Mexico Museum of Natural History and Science Bulletin 35, p. 105–113.

Milner, A.R.C., and Spears, S.Z., 2007, Mesozoic and Cenozoic paleoichnology of southwestern Utah, *in* Lund, W.R., editor, Field guide to geologic excursions in southern Utah: Utah Geological Association Publication 35, 85 p. on CD.

Mohn, K.W., 1986, Stratigraphy and tectonic development of the Parowan Gap area, Iron County, Utah: Stephen F. Austin State University, 129 p., 2 plates, scale 1:21,478.

Moore, D.W., 1992, Origin of breccia of the Isom Formation near Cedar Breaks National Monument, Markagunt Plateau, southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 24, no. 6, p. 54.

Moore, D.W., and Nealey, L.D., 1993, Preliminary geologic map of the Navajo Lake quadrangle, Kane and Iron Counties, Utah: U.S. Geological Survey Open-File Report 93-190, 20 p., 1 plate, scale 1:24,000.

Moore, D.W., Nealey, L.D., Rowley, P.D., Hatfield, S.C., Maxwell, D.J., and Mitchell, E., 2004, Geologic map of the Navajo Lake quadrangle, Kane and Iron Counties, Utah: Utah Geological Survey Map 199, 2 plates, scale 1:24,000.

Moore, D.W., Nealey, L.D., and Sable, E.G., 1994, Preliminary report, measured sections, and map of the geology of the Asay Bench quadrangle, Garfield and Kane Counties, Utah: U.S. Geological Survey Open-File Report 94-10, 26 p., 1 plate, scale 1:24,000.

Moore, D.W., and Straub, A.W., 1995, Preliminary geologic map of the Panguitch quadrangle, Garfield County, Utah: U.S. Geological Survey Open-File Report 95-9, 13 p., 1 plate, scale 1:24,000.

Moore, D.W., and Straub, A.W., 2001, Correlation of Upper Cretaceous and Paleogene(?) rocks beneath the Claron Formation, Crow Creek, western Markagunt Plateau, southwest Utah, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin—symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists, Utah Geological Association Publication 30, p. 75–95.

Mullett, D.J., 1989, Interpreting the early Tertiary Claron Formation of southern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 120.

Mullett, D.J., and Wells, N.A., 1990, Soil fabrics and horizontal cracking in the Paleogene Claron Formation of southern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 7, p. 335.

Mullett, D.J., Wells, N.A., and Anderson, J.J., 1988a, Early Cenozoic deposition in the Cedar-Bryce depocenter—certainties, uncertainties, and comparisons with other Flagstaff-Green River basins [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 3, p. 217.

Mullett, D.J., Wells, N.A., and Anderson, J.J., 1988b, Unusually intense pedogenic modification of the Paleocene-Eocene Claron Formation of southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 5, p. 382.

Mulvey, W.E., Currey, D.R., and Lindsay, L.M.W., 1984, Southernmost occurrence of later Pleistocene glaciations in Utah – Brian Head-Signey [sic] Peaks area, Markagunt Plateau: Encyclia, v. 61, p. 97–104.

Nealey, L.D., Budahn, J.R., Maldonado, F., and Unruh, D.M., 1997, Geochemistry and petrogenesis of Quaternary basaltic rocks from the Red Hills and western Markagunt Plateau, southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range-Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153-I, p. 177–198.

Nealey, L.D., Unruh, D.M., Ludwig, K.R., and Maldonado, F., 1995, Three-dimensional analysis of Sr-Nd-Pb isotopic data for upper Cenozoic volcanic rocks, Colorado Plateau-Basin and Range transition zone [abs.]: EOS, Transactions, American Geophysical Union, v. 76, no. 46, p. 687.

Nelson, S.T., and Tingey, D.G., 1997, Time-transgressive and extension-related basaltic volcanism in southwest Utah and vicinity: Geological Society of America Bulletin, v. 109, no. 10, p. 1249–1265.

Nickelsen, R.P., and Merle, O., 1991, Structural evolution at the tip line of a mid-Tertiary compressional event in south-western Utah [abs.]: Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 109.

Nickelsen, R.P., Merle, O., and Davis, G.H., 1992, Structures of the mid-Tertiary radial compression in the High Plateaus of southern Utah in relation to Sevier, Laramide, and Basin and Range deformation [abs.]: Geological Society of America Abstracts with Programs, v. 24, no. 6, p. 55.

Nichols, D.J., 1997, Palynology and ages of some Upper Cretaceous formations in the Markagunt and northwestern Kaiparowits Plateaus, southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range-Colorado Plateau transition zone in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153-E, p. 81–95.

Nusbaum, R.L., Unruh, D.M., and Millings, V.E., III, 1997, The role of lithosphere and asthenosphere in the genesis of late Cenozoic volcanism at Diamond Valley and Veyo volcano, southwest Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range-Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153-K, p. 229–239.

Ott, A.L., 1999, Detailed stratigraphy and stable isotope analysis of the Claron Formation, Bryce Canyon National Park, southwestern Utah: Pullman, Washington State University, M.S. thesis, 130 p.

Palmer, W.R., 1957, Why the North Star stands still and other Indian legends: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 118 p.

Peterson, F., 1969, Four new members of the Upper Cretaceous Straight Cliffs Formation in southeastern Kaiparowits region, Kane County, Utah: U.S. Geological Survey Bulletin 1274-J, p. 1–28.

Peterson, F., 1988, Stratigraphy and nomenclature of Middle and Upper Jurassic rocks , western Colorado Plateau, Utah and Arizona: U.S. Geological Survey Bulletin 1633-B, p. B13–B56.

Peterson, F., 1994, Sand dunes, sabkhas, streams, and shallow seas—Jurassic paleogeography in the southern part of the Western Interior basin, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Colorado, Rocky Mountain Section of the Society for Sedimentary Geology, p. 233–272.

Petit, J.P., 1987, Criteria for the sense of movement on fault surfaces in brittle rocks: Journal of Structural Geology, v. 9, no. 5/6, p. 597–608.

Pipiringos, G.N., and O'Sullivan, R.B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United State—a preliminary survey: U.S. Geological Survey Professional Paper 1035-A, 29 p.

Pollock, S.L., 1999, Provenance, geometry, lithofacies, and age of the Upper Cretaceous Wahweap Formation, Cordilleran foreland basin, southern Utah: Las Cruces, New Mexico State University, M.S. thesis, 117 p.

Quick, J.C., 2010, Quality of the Smirl coal, Alton coalfield, Kane County, Utah, *in* Carney, S.M., Tabet, D.E., and Johnson, C.L., editors, Geology and geologic resources of south-central Utah: Utah Geological Association Guidebook 39, p. 367–380.

Rahl, J.M., Reiners, P.W., Campbell, I.H., Nicolescu, S., and Allen, C.M., 2003, Combined single-grain (U-Th)/He and U-Pb dating of detrital zircons from the Navajo Sandstone, Utah: Geology, v. 31, no. 9, p. 761–764.

Reiners, P.W., Campbell, I.H., Nicolescu, S., Allen, C.M., Hourigan, J.K., Garver, J.I., Mattinson, J.M., and Cowan, D.S., 2005, (U-Th)/(He-Pb) double-dating of detrital zircons: American Journal of Science, v. 305, p. 259–311.

Riggs, N.R., Mattinson, J.M., and Busby, C.J., 1993, Correlation of Jurassic eolian strata between the magmatic arc and the Colorado Plateau—new U-Pb geochronologic data from southern Arizona: Geological Society of America Bulletin, v. 105, p. 1231–1246.

Roberts, E.M., 2007, Facies architecture and depositional environments of the Upper Cretaceous Kaiparowits Formation, southern Utah: Sedimentary Geology, v. 197, p. 207–233.

Roberts, E.M., Deino, A.L., and Chan, M.A., 2005, $^{40}Ar/^{39}Ar$ age of the Kaiparowits Formation, southern Utah, and correlation of contemporaneous Campanian strata and vertebrate faunas along the margin of the Western Interior Basin: Cretaceous Research, v. 26, p. 307–318.

Robison, R.A., 1966, Geology and coal resources of the Tropic area, Garfield County, Utah: Utah Geological and Mineralogical Survey Special Studies v. 18, scale 1:24,000, 47 p.

Rowley, P.D., 1968, Geology of the southern Sevier Plateau, Utah: Austin, University of Texas, Ph.D. dissertation, 1 plate, scale 1:62,500, 385 p.

Rowley, P.D., 1998, Cenozoic transverse zones and igneous belts in the Great Basin, western United States – their tectonic and economic implications, *in* Faulds, J.E., and Stewart, J.H., editors, Accommodation zones and transfer zones—the regional segmentation of the Basin and Range Province: Geological Society of America Special Paper 323, p. 195–228.

Rowley, P.D., Anderson, J.J., and Williams, P.L., 1975, A summary of Tertiary volcanic stratigraphy of the southwestern High Plateaus and adjacent Great Basin, Utah: U.S. Geological Survey Bulletin, 1405-B, 20 p.

Rowley, P.D., and Barker, D.S., 1978, Geology of the Iron Springs mining district, Utah, *in* Shawe, D.R., and Rowley, P.D., editors, Guidebook to mineral deposits of southwestern Utah: Utah Geological Association Publication 7, p. 49–58.

Rowley, P.D., Cunningham, C.G., and Kaplan, A.M., 1981, Geologic map of the Monroe SE quadrangle, Piute and Sevier Counties, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1331, scale 1:24,000.

Rowley, P.D., Cunningham, C.G., Steven, T.A., Mehnert, H.H., and Naeser, C.W., 1998, Cenozoic igneous and tectonic setting of the Marysvale volcanic field, and its relation to other igneous centers in Utah and Nevada, *in* Friedman, J.D., and Huffman, A.C., Jr., coordinators, Laccolith complexes of southeastern Utah – time of emplacement and tectonic setting—workshop proceedings: U.S. Geological Survey Bulletin 2158, p. 167–202.

Rowley, P.D., Cunningham, C.G., Steven, T.A., Workman, J.B., Anderson, J.J., and Theissen, K.M., 2002, Geologic map of the central Marysvale volcanic field, southwestern Utah: U.S. Geological Survey Geologic Investigations Series Map I-2645-A, scale 1:100,000.

Rowley, P.D., and Dixon, G.L., 2001, The Cenozoic evolution of the Great Basin area, U.S.A.—new interpretations based on regional geologic mapping, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin—a symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists, Utah Geological Association Publication 30, p. 169–188.

Rowley, P.D., Hereford, R., and Williams, V.S., 1987, Geologic map of the Adams Head-Johns Valley area, southern Sevier Plateau, Garfield County, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1798, 1 plate, scale 1:50,000.

Rowley, P.D., Mehnert, H.H., Naeser, C.W., Snee, L.W., Cunningham, C.G., Steven, T.A., Anderson, J.J., Sable, E.G., and Anderson, R.E., 1994a, Isotopic ages and stratigraphy of Cenozoic rocks of the Marysvale volcanic field and adjacent areas, west-central Utah: U.S. Geological Survey Bulletin 2071, 35 p.

Rowley, P.D., Nealey, L.D., Unruh, D.M., Snee, L.W., Mehnert, H.H., Anderson, R.E., and Gromme, C.S., 1995, Stratigraphy of Miocene ash-flow tuffs in and near the Caliente caldera complex, southeastern Nevada and southwestern Utah, *in* Scott, R.B., and Swadley, W C, editors, Geologic studies in the Basin and Range – Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1992: U.S. Geological Survey Bulletin 2056, p. 43–88.

Rowley, P.D., Sable, E.G., Boswell, J.T., Vice, G.S., Hatfield, S.C., Maxwell, D.J., Lund, W.R., Anderson, J.J., and Biek, R.F., in preparation, Geologic map of the Brian Head quadrangle, Iron County, Utah: Utah Geological Survey Map, scale 1:24,000.

Rowley, P.D., Shroba, R.R., Simonds, F.W., Burke, K.J., Axen, G.J., and Olmore, S.D., 1994b, Geologic map of the Chief Mountain quadrangle, Lincoln County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1731, scale 1:24,000.

Rowley, P.D., Steven, T.A., Anderson, J.J., and Cunningham, C.G., 1979, Cenozoic stratigraphic and structural framework of southwestern Utah: U.S. Geological Survey Professional paper 1149, 22 p.

Rowley, P.D., Steven, T.A., and Mehnert, H.H., 1981, Origin and structural implications of upper Miocene rhyolites in Kingston Canyon, Piute County, Utah: Geological Society of America Bulletin, Part I, v. 92, p. 590–602.

Rowley, P.D., and Threet, R.L., 1976, Geologic map of the Enoch quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-1296, scale 1:24,000; modified by P.D. Rowley, 2003.

Rowley, P.D., Vice, G.S., McDonald, R.E., Anderson, J.J., Machette, M.N., Maxwell, D.J., Ekren, E.B., Cunningham, C.G., Steven, T.A., and Wardlaw, B.R., 2005, Interim geologic map of the Beaver 30' x 60' quadrangle, Beaver, Piute, Iron, and Garfield Counties, Utah: Utah Geological Survey Open-File Report 454, 27 p., 1 plate, scale 1:100,000.

Rowley, P.D., Williams, V.S., Vice, G.S., Maxwell, D.J., Hacker, D.B., Snee, L.W., and Mackin, J.H., 2008, Interim geologic map of the Cedar City 30' x 60' quadrangle, Iron and Washington Counties, Utah: Utah Geological Survey Open-File Report 476DM, scale 1:100,000.

Sable, E.G., and Hereford, R., 2004, Geologic map of the Kanab 30' x 60' quadrangle, Utah and Arizona: U.S. Geological Survey Geologic Investigations Series I-2655, scale 1:100,000.

Sable, E.G., and Maldonado, F., 1997a, Breccias and megabreccias, Markagunt Plateau, southwestern Utah—origin, age, and transport directions, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range-Colorado Plateau transition zone in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 151–176.

Sable, E.G., and Maldonado, F., 1997b, The Brian Head Formation (revised) and selected Tertiary sedimentary rock units, Markagunt Plateau and adjacent areas, southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range-Colorado Plateau transition zone in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 7–26.

Sargent, K.A., and Hansen, D.E., 1982, Bedrock geologic map of the Kaiparowits coal-basin area, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1033-I, 1 plate, scale 1:125,000.

Schneider, M.C., 1967, Early Tertiary continental sediments of central and south-central Utah: Brigham Young University Geology Studies, v. 14, p. 143–194.

Schulman, E., 1956, Dendroclimatic changes in semiarid America: Tucson, University of Arizona Press, 142 p.

Sharp, W.D., Ludwig, K.R., Chadwick, O.A., Amundson, R., and Glaser, L.L., 2003, Dating fluvial terraces by ^{230}Th/U on pedogenic carbonate, Wind River Basin, Wyoming: Quaternary Research, v. 59, p. 139–150.

Smith, E.I., Sanchez, A., Walker, J.D., and Wang, K., 1999, Geochemistry of mafic magmas in the Hurricane volcanic field, Utah—implications for small- and large-scale chemical variability of the lithospheric mantle: The Journal of Geology, v. 107, p. 433–448.

Spangler, L.E., 2010, Geology and hydrology of a vulcanokarstic terrain on the Markagunt Plateau, southwestern Utah, *in* Carney, S.M., Tabet, D.E., and Johnson, C.L., editors, Geology and geologic resources of south-central Utah: Utah Geological Association Guidebook 39, p. 93–108.

Sprinkel, D.A., 2009, Interim geologic map of the Seep Ridge 30' x 60' quadrangle, Uinta, Duchesne, and Carbon Counties, Utah, and Rio Blanco and Garfield Counties, Colorado: Utah Geological Survey Open-File Report 549DM, 3 plates, scale 1:100,000.

Sprinkel, D.A., Doelling, H.H., Kowallis, B.J., Waanders, G., and Kuehne, P.A., 2011a, Early results of a study of Middle Jurassic strata in the Sevier fold and thrust belt, Utah, *in* Sprinkel, D.A., Yonkee, W.A., and Chidsey. T.C., Jr., editors, Sevier thrust belt—northern and central Utah and adjacent areas: Utah Geological Association Publication 40, p. 151–172.

Sprinkel, D.A., Kowallis, B.J., and Jensen, P.H., 2011b, Correlation and age of the Nugget Sandstone and Glen Canyon Group, Utah, *in* Sprinkel, D.A., Yonkee, W.A., and Chidsey. T.C., Jr., editors, Sevier thrust belt—northern and central Utah and adjacent areas: Utah Geological Association Publication 40, p. 131–149.

Sprinkel, D.A., Kowallis, B.J., Waanders, G., Doelling, H.H., and Kuehne, P.A., 2009, The Middle Jurassic Temple Cap Formation, southern Utah—radiometric age, palynology, and correlation with the Gypsum Spring Member of the Twin Creek Limestone and Harris Wash Member of the Page Sandstone [abs.]: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 690.

Spurney, J.C., 1982, The origin and characteristics of magnetite in the Iron Peak laccolith, Markagunt Plateau, Utah [abs.]: Geological Society of America Abstracts with Programs, v.14, no.6, p.350.

Spurney, J.C., 1984, Geology of the Iron Peak intrusion, Iron County, Utah: Kent, Ohio, Kent State University, M.S. thesis, 84 p., 8 plates, scale 1:16,500.

Steven, T.A., 1981, Three Creeks caldera, southern Pahvant Range, Utah: Brigham Young University Geology Studies, v. 28, part 3, p. 1–7.

Steven, T.A., Cunningham, C.G., Naeser, C.W., and Mehnert, H.H., 1979, Revised stratigraphy and radiometric ages of volcanic rocks and mineral deposits in the Marysvale area, west-central Utah: U.S. Geological Survey Bulletin 1469, 40 p.

Steven, T.A., Rowley, P.D., and Cunningham, C.G., 1984, Calderas of the Marysvale volcanic field, west-central Utah: Journal of Geophysical Research, v. 89, no. B10, p. 8751–8764.

Stowell, S.L., 2006, Volcanology and petrogenesis of the Navajo Lake volcanic field: Las Vegas, University of Nevada, M.S. thesis, 87 p.

Strong, M.F., 1984, Brianhead agate at Cedar Breaks: Jewelry Making Gems & Minerals, v. 562, p. 10–11.

Taylor, W.J., 1993, Stratigraphic and lithologic analysis of the Claron Formation in southwestern Utah: Utah Geological Survey Miscellaneous Publication 93-1, 52 p.

Thompson, A.E., and Stokes, W.L., 1970, Straigraphy of the San Rafael Group, southwest and south central Utah: Utah Geological and Mineralogical Survey Bulletin 87, 53 p.

Threet, R.L., 1952, Geology of the Red Hills area, Iron County, Utah: Seattle, University of Washington, Ph.D. dissertation, 1 plate, scale 1:62,500, 107 p.

Threet, R.L., 1963, Geology of the Parowan Gap area, Iron County, Utah, *in* Heylmun, E.B., editor, Guidebook to the geology of southwestern Utah—transition between the Basin-Range and Colorado Plateau Provinces: Salt Lake City, Utah, Intermountain Association of Petroleum Geologists, Twelfth Annual Field Conference, p. 136–145.

Tibert, N.E., Leckie, R.M., Eaton, J.G., Kirkland, J.I., Colin, J.P., Leithold, E.L., and McCormic, M.E., 2003, Recognition of relative sea-level change in Upper Cretaceous coal-bearing strata—a paleoecological approach using agglutinated foraminifera and ostracods to detect key stratigraphic surfaces, *in* Olson, H.C., and Leckie, R.M., editors, Micropaleontological proxies for sea-level change and stratigraphic discontinuities: Society of Economic Paleontologists and Mineralogists Special Publication no. 75, p. 263–299.

Tilton, T.L., 1991, Upper Cretaceous stratigraphy of the southern Paunsaugunt Plateau, Kane County, Utah: Salt Lake City, University of Utah, Ph.D. dissertation, 2 plates, scale 1:24,000, 162 p.

Tilton, T.L., 2001a, Geologic map of the Alton quadrangle, Kane County, Utah: Utah Geological Survey Miscellaneous Publication 01-4, 22 p., 2 plates, scale 1:24,000.

Tilton, T.L., 2001b, Geologic map of the Podunk Creek quadrangle, Kane County, Utah: Utah Geological Survey Miscellaneous Publication 01-3, 18 p., 2 plates, scale 1:24,000.

Titus, A.L., Powell, J. D., Roberts, E.M., Sampson, S.D., Pollock, S.L., Kirkland, J.I., and Albright, L.B., 2005. Late Cretaceous stratigraphy, depositional environments, and macrovertebrate paleontology of the Kaiparowits Plateau, Grand Staircase-Escalante National Monument, Utah, *in* Pederson, J., and Dehler, C.M., editors., Interior Western United States: Geological Society of America Field Guide 6, p. 101–128.

Titus, A.L., Roberts, E.M., and Albright, L.B., in press, Geologic overview—at the top of the Grand Staircase: the Late Cretaceous of southern Utah, *in* Titus, A.L., editor: Indiana University Press.

Thomas, J.B., 1985, The stratigraphy, sedimentology, and petrology of the early Tertiary Claron Formation in the Red Canyon area of the south-central High Plateaus, Utah: Kent, Ohio, Kent State University, M.S. thesis, 135 p.

Tschudy, R.H., Tschudy, B.D., and Craig, L.C., 1984, Palynological evaluation of Cedar Mountain and Burro Canyon Formations, Colorado Plateau: U.S. Geological Survey Professional Paper 1281, 24 p., 9 plates.

Utah Geological Survey and Nevada Isotope Geochronology Laboratory (UGS and NIGL), 2012, $^{40}Ar/^{39}Ar$ geochronology results for the Gooseberry Creek, Haycock Mountain, Mercur, Stockton, and Tabbys Peak quadrangles, Utah: Utah Geological Survey Open-File Report 590, variously paginated, also available online, http://geology.utah.gov/online/ofr/ofr-590.pdf.

Utah Geological Survey and New Mexico Geochronology Research Laboratory (UGS and NMGRL), 2008, $^{40}Ar/^{39}Ar$ geochronology results from the Cogswell Point, Dog Valley Peak, Little Drum Pass, Red Ridge, Rex Reservoir, Sage Valley, and Smelter Knolls West quadrangles, Utah: Utah Geological Survey Open-File Report 522, variously paginated, also available online, http://geology.utah.gov/online/ofr/ofr-522.pdf.

Utah Geological Survey and New Mexico Geochronology Research Laboratory (UGS and NMGRL), 2009, $^{40}Ar/^{39}Ar$ geochronology results for the Blind Lake, Deer Creek Lake, Flat Top, Henrie Knolls, Tabbys Peak, Tabbys Peak SW, Wig Mountain, and Wig Mountain NE quadrangles, Utah: Utah Geological Survey Open-File Report 547, variously paginated, also available online, http://geology.utah.gov/online/ofr/ofr-547.pdf.

Utah Geological Survey and New Mexico Geochronology Research Laboratory (UGS and NMGRL), 2012, $^{40}Ar/^{39}Ar$ geochronology results for the Gooseberry Creek, Haycock Mountain, Mercur, Stockton, and Tabbys Peak quadrangles, Utah: Utah Geological Survey Open-File Report 590, 25 p., also available online, http://geology.utah.gov/online/ofr/ofr-590.pdf.

Van Kooten, G.K., 1988, Structure and hydrocarbon potential beneath the Iron Springs laccolith, southwestern Utah: Geological Society of America Bulletin, v. 100, p. 1533–1540.

Wagner, J.J., 1984, Geology of the Haycock Mountain 7.5-minute quadrangle, western Garfield County, Utah: Kent, Ohio, Kent State University, M.S. thesis, 68 p., 1 plate, scale 1:24,000.

Weaver, W.J., IV, Marchetti, D.W., Stoll, D.K., Harris, M.S., and Bailey, C.M., 2006, ^{3}He exposure ages for glacial deposits, Fish Lake Plateau, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 38, no. 6, p. 30.

Williams, P.L., 1967, Stratigraphy and petrography of the Quichapa Group, southwestern Utah and southeastern Nevada: Seattle, University of Washington, Ph.D. dissertation, 141 p.

Williams, V.S., 1985, Surficial geologic map of the Kaiparowits coal-basin area. Utah: U.S. Geological Survey Miscellaneous Investigations Map I-1033-L, 1 plate, scale 1:125,000.

Williams, V.S., and Maldonado, F., 1995, Quaternary geology and tectonics of the Red Hills area of the Basin and Range-Colorado Plateau Transition Zone, Iron County, Utah, *in* Scott, R.B., and Swadley, W C, editors, Geologic studies in the Basin and Range – Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1992: U.S. Geological Survey Bulletin 2056, p. 257–275.

Willis, G.C., 1999, The Utah thrust system—an overview, *in* Spangler, L.E., and Allen, C.J., editors, Geology of northern Utah and vicinity: Utah Geological Association Publication 27, p. 1–9.

Willis, G.C., 2002, Massive gravity slides show the value of detailed mapping: Utah Geological Survey, Survey Notes, v. 34, no. 3, p. 1–3.

Willis, G.C., Biek, R.F., and Hayden, J.M., 2006, New age of the Santa Clara (Snow Canyon State Park) basalt flow: Utah Geological Survey, Survey Notes, v. 38, no. 3, p. 4–5.

Wilson, M.T., and Thomas, H.E., 1964, Hydrology and hydrogeology of Navajo Lake, Kane County, Utah: U.S. Geological Survey Professional Paper 417-C, 26 p.

Yannacci, D.S., 1986, The Buckskin Breccia—a block and ash-flow tuff of Oligocene age in the southwestern High Plateaus of Utah: Kent, Ohio, Kent State University, M.S. thesis, 107 p.

Table 1. 40Ar/39Ar, K-Ar, and U-Pb ages of volcanic rocks, Panguitch 30' x 60' quadrangle and adjacent area.

Lava Flow or Formation	Map Symbol	Sample number	K-Ar age (Ma)	K-Ar age (Ma) (corrected)	$^{40}Ar/^{39}Ar$ age (Ma)	U-Pb age (Ma)	Mineral	7.5' Quadrangle	Longitude	Latitude	Lab used	Reference	Comments
Asay Knoll	Qbak	pan-5	0.52 ± 0.05				whole rock	Asay Bench	-112.5481	37.5525	USGS	Best and others (1980)	also used labs at BYU and UofA - Tucson
Bauers Tuff	Tqcb	R-11	22.1 ± 0.6	22.7 ± 0.6			plagioclase	Fivemile Ridge	-112.5167	37.8333	Ohio State University	Fleck and others (1975)	
Bear Valley Fm.	Tbv	R-10	24.0 ± 0.4	24.6 ± 0.4			biotite	Fivemile Ridge	-112.5333	37.8700	Ohio State University	Fleck and others (1975)	tuff
Bear Valley Fm.	Tbv	R-9	23.9 ± 0.5	24.5 ± 0.5			plagioclase	Fivemile Ridge	-112.5600	37.8617	Ohio State University	Fleck and others (1975)	vitric ignimbrite
Black Mountain	Qbbm	C-350-5	0.80 ± 0.24				whole rock	Webster Flat	-112.9592	37.5889	USGS	Anderson and Mehnert (1979)	
Black Mountain	Qbbm	zion-63	0.87 ± 0.04				whole rock	Webster Flat	-112.9372	37.5675	USGS	Best and others (1980)	also used labs at BYU and UofA - Tucson
Blue Spring Mountain	Tbbm	626BS1			2.78 ± 0.16		whole rock	Panguitch Lake	-112.6700	37.6700	NIGL	Stowell (2006)	location imprecise
Brian Head Fm.	Tbh	BH062310-1				35.77 ± 0.28	zircon	Brian Head	-112.8302	37.6548	AtoZ	Biek and others (in prep.)	base of formation
Brian Head Fm.	Tbh	CC101310-1				36.51 ± 1.69	zircon	Casto Canyon	-112.2570	37.8196	AtoZ	Biek and others (in prep.)	about 80' above base of formation
Brian Head Fm.	Tbh	HM111810-1				34.95 ± 0.83	zircon	Haycock Mountain	-112.5522	37.7059	AtoZ	Biek and others (in prep.)	same as HM071809-2
Brian Head Fm.	Tbh	HM11810-2				33.55 ± 0.80	zircon	Haycock Mountain	-112.5502	37.7066	AtoZ	Biek and others (in prep.)	same as HM071809-4
Brian Head Fm.	Tbh					34.7 ± 0.6	zircon	Brian Head	-112.8311	37.6811	unknown	Davis and others (2008)	Brian Head peak
Brian Head Fm.	Tbh					35.2 ± 0.8	zircon	Brian Head	-112.8311	37.6811	unknown	Davis and others (2008)	Brian Head peak
Brian Head Fm.	Tbh	HM071809-2			35.04 ± 0.05**		sanidine	Haycock Mountain	-112.5522	37.7059	NIGL	Biek and others (in prep.)	
Brian Head Fm.	Tbh	HM071809-4			33.80 ± 0.05**		sanidine	Haycock Mountain	-112.5502	37.7066	NIGL	Biek and others (in prep.)	
Brian Head Fm.	Tbh	93USa10a			34.99 ± 0.22***		biotite	George Mountain	-112.4700	37.5872	NMGRL	Sable unpublished data (1996)	excess Ar; unusual K/Ca ratio
Brian Head Fm., tuff	Tbht	Rh-573	26.3 ± 1.3				biotite	Parowan Gap	-112.8750	37.9772	USGS (Mehnert)	Sable unpublished data (1992)	see also Maldonado and Moore (1995)
Brian Head Fm., tuff	Tbht	Rh-573	34.2 ± 2.1				plagioclase	Parowan Gap	-112.8750	37.9772	USGS (Mehnert)	Sable unpublished data (1992)	see also Maldonado and Moore (1995)
Brian Head Fm., tuff	Tbht	Rh-573			33.00 ± 0.13		plagioclase	Parowan Gap	-112.8750	37.9772	USGS (Snee)	Sable unpublished data (1994)	see also Maldonado and Moore (1995)
Brian Head Fm., tuff	Tbht	Rh-573			33.70 ± 0.14		biotite	Parowan Gap	-112.8750	37.9772	USGS (Snee)	Sable unpublished data (1994)	see also Maldonado and Moore (1995)
Dickinson Hill	Tbdh	AC-PANG	5.3 ± 0.5				whole rock	Panguitch	-112.4292	37.8000	USGS	Rowley and others (1994a)	approximate coordinates; NE wall DD Hollow
Haycock Mountain Tuff (type section)	Thm	94UPh-Thm2			22.75 ± 0.12		sanidine	Haycock Mountain	-112.6083	37.7300	NMGRL	Sable unpublished data (1996)	approximate location
Henrie Knolls	Qbhk	HK092106-1			0.058 ± 0.036*		whole rock	Henrie Knolls	-112.6595	37.5903	NMGRL	Biek and others (2011)	
Houston Mountain	Tbhm	HK092006-3			5.27 ± 0.14		whole rock	Henrie Knolls	-112.7232	37.6175	NMGRL	Biek and others (2011)	
Iron Peak laccolith	Tip	R-28	19.7 ± 0.5	20.2 ± 0.5			whole rock	Cottonwood Mountain	-112.7017	37.8483	Ohio State University	Fleck and others (1975)	latitude uncertain; possibly 37.9111
Iron Peak lava flow?	Tipl?	R-27	20.7 ± 0.5	21.2 ± 0.5			whole rock	Red Creek Reservoir?	-112.6767	37.7550	Ohio State University	Fleck and others (1975)	location uncertain
Isom Fm. (Bald Hills Tuff Mbr.)	Ti	R-8	25.0 ± 0.4	25.7 ± 0.4			plagioclase	Fivemile Ridge	-112.5667	37.8550	Ohio State University	Fleck and others (1975)	
Isom Fm. (Blue Meadows Tuff Mbr.)	Ti	R-7	25.2 ± 0.4	25.9 ± 0.4			plagioclase	Panguitch NW	-112.4333	37.9700	Ohio State University	Fleck and others (1975)	
Leach Canyon Fm.	Tql	89USa1a	22.8 ± 1.1				biotite	Panguitch Lake	-112.6944	37.7003	USGS (Mehnert)	Rowley and others (1994)	Haycock Mtn. Tuff of Rowley and others (1994)
Leach Canyon Fm.	Tql	89USa1a	24.3 ± 1.0				sanidine (rerun)	Panguitch Lake	-112.6944	37.7003	USGS (Mehnert)	Sable and Maldonado (1997)	Haycock Mtn. Tuff of Rowley and others (1994)
Leach Canyon Fm.	Tql	89USa1a	24.8 ± 1.0				sanidine	Panguitch Lake	-112.6944	37.7003	USGS (Mehnert)	Rowley and others (1994a)	Haycock Mtn. Tuff of Rowley and others (1994)
Leach Canyon Fm.	Tql	89USa1a			23.86 ± 0.26		biotite	Panguitch Lake	-112.6833	37.7083	USGS (Snee)	Sable and Maldonado (1997)	Haycock Mtn. Tuff of Rowley and others (1994)
Limerock Canyon Fm.	Tl	H111810-1				20.52 ± 0.49	zircon	Hatch	-112.4721	37.6588	AtoZ	Biek and others (in prep.)	
Limerock Canyon Fm.	Tl	LT-1B-89	19.8 ± 0.8				sanidine	Hatch	-112.4681	37.6569	USGS (Mehnert)	Sable and Maldonado (1995)	also see Kurlich and Anderson (1997)
Limerock Canyon Fm.	Tl	LT-1B-89	20.2 ± 1.4				biotite	Hatch	-112.4681	37.6569	USGS (Mehnert)	Sable and Maldonado (1995)	also see Kurlich and Anderson (1997)
Limerock Canyon Fm.	Tl	LT-2-89			20.48 ± 0.8		biotite	Hatch	-112.4681	37.6569	USGS (Snee)	Sable and Maldonado (1995)	
Limerock Canyon Fm.	Tl	LT-4-89	21.0 ± 1.0				sanidine	Hatch	-112.4778	37.6444	USGS (Mehnert)	Sable and Maldonado (1995)	also see Kurlich and Anderson (1997)
Limerock Canyon Fm.	Tl	LT-4-89	21.5 ± 0.6				biotite	Hatch	-112.4778	37.6444	USGS (Mehnert)	Sable and Maldonado (1995)	also see Kurlich and Anderson (1997)
Long Flat	Qblf	LEA71SS2			0.60 ± 0.25		whole rock	Brian Head	-112.7500	37.6600	NIGL	Stowell (2006)	location imprecise
Mount Dutton Fm.	Td	R-5	25.1 ± 0.7	25.8 ± 0.7			whole rock	Little Creek Peak	-112.5783	37.9517	Ohio State University	Fleck and others (1975)	
Pine Spring Knoll		C-311-34	1.06 ± 0.28				whole rock	Cedar Mountain	-113.1028	37.5625	USGS	Anderson and Mehnert (1979)	vent (source) uncertain; overlies Ta
post-Claron tuff		R-4	31.1 ± 0.5	31.9 ± 0.5			biotite	Burnt Peak	-112.5917	38.0067	Ohio State University	Fleck and others (1975)	
Red Canyon	Qbrc	pan-28	0.56 ± 0.07				whole rock	Wilson Peak	-112.3333	37.7447	USGS	Best and others (1980)	also used labs at BYU and UofA - Tucson
Red Canyon	Qbrc	SF-2			0.49 ± 0.04**		whole rock	Wilson Peak	-112.3292	37.7544	NMGRL	Lund and others (2008)	footwall; maximum age
Red Canyon	Qbrc	SF-6			0.51 ± 0.01**		whole rock	Wilson Peak	-112.3284	37.7525	NMGRL	Lund and others (2008)	hanging wall
Red Hills	Qbrh	C342-5A	1.28 ± 0.4				whole rock	Parowan Gap	-112.9875	37.8833	USGS	Anderson and Mehnert (1979)	reported as 1.3 ± 0.3 (Best and others, 1980)
rhyolite tuff (Leach Canyon Fm.?)	Trt	89USa2a	15.8				glass	Haycock Mountain	-112.5790	37.7170	USGS (Mehnert)	Sable unpublished data (1992)	unsuitable; basal vitrophyre of Haycock Mtn. Tuff of Rowley and others (1994)
rhyolite tuff (Leach Canyon Fm.?)	Trt	89USa2a	22.3 ± 1.1				plagioclase	Haycock Mountain	-112.5790	37.7170	USGS (Mehnert)	Sable and Maldonado (1997)	basal vitrophyre of Haycock Mtn. Tuff of Rowley and others (1994)
rhyolite tuff (Leach Canyon Fm.?)	Trt	89USa2a			24.23 ± 0.17		plagioclase	Haycock Mountain	-112.5790	37.7170	USGS (Snee)	Sable and Maldonado (1997)	basal vitrophyre of Haycock Mtn. Tuff of Rowley and others (1994)
Rock Canyon	Tbrc	SF-4			4.94 ± 0.03**		whole rock	Wilson Peak	-112.3089	37.7241	NMGRL	Lund and others (2008)	footwall
Rock Canyon	Tbrc	SF-7			4.98 ± 0.03**		whole rock	Wilson Peak	-112.3304	37.7402	NMGRL	Lund and others (2008)	hanging wall
Spry intrusion	Tis	BRP110410-1				26.24 ± 0.62	zircon	Bull Rush Peak	-112.3597	37.0244	AtoZ	Biek and others (in prep.)	Hwy 89 road cut exposure
Spry intrusion	Tis	84-257	26.1 ± 1.8				plagioclase	Bull Rush Peak	-112.3556	38.0361	USGS	Rowley and others (1994a)	Hwy 89 road cut exposure
Summit	Qbs	C-1730-8A	0.94 ± 0.14				whole rock	Summit	-112.9592	37.7700	USGS	Anderson and Mehnert (1979)	
Summit	Qbs	C-1730-9	1.00 ± 0.16				whole rock	Summit	-112.9597	37.7733	USGS	Anderson and Mehnert (1979)	incorrectly listed as 112 58 35
volcanic rocks of Bull Rush Creek - dike		84-259	26.4 ± 3.2				plagioclase	Bull Rush Peak	-112.3236	38.0319	USGS	Rowley and others (1994a)	derived from Spry intrusion
volcanic rocks of Bull Rush Creek - dike		84-259	29.4 ± 2.2				horneblende	Bull Rush Peak	-112.3236	38.0319	USGS	Rowley and others (1994a)	derived from Spry intrusion
Wah Wah Springs Fm.	Tnw	USA60A	30.4 ± 1.1				horneblende	Brian Head	-112.7967	37.6811	USGS (Mehnert)	Rowley and others (1994a)	
Wah Wah Springs Fm.	Tnw	USA60A	30.4 ± 3.1				biotite	Brian Head	-112.7967	37.6811	USGS (Mehnert)	Rowley and others (1994a)	
Wah Wah Springs Fm.	Tnw	R-25	28.7 ± 0.5				biotite	Brian Head	-112.7667	37.7067	Ohio State University	Fleck and others (1975)	
Wah Wah Springs Fm.	Tnw	USA60B	29.1 ± 1.0				horneblende	Brian Head	-112.7967	37.6811	USGS (Mehnert)	Rowley and others (1994a)	
Wah Wah Springs Fm.	Tnw	USA60B	32.4 ± 3.4				biotite	Brian Head	-112.7967	37.6811	USGS (Mehnert)	Rowley and others (1994a)	
Water Canyon	Qbw	R-29	0.44 ± 0.04	0.45 ± 0.04			whole rock	Parowan	-112.7733	37.8633	Ohio State University	Fleck and others (1975)	
Wood Knoll	Qbwk	CCB	0.63 ± 0.10				whole rock	Flanigan Arch	-112.9339	37.6350	NMGRL	Lund and others (2007)	approximate location

NOTES:

Map Symbol is the symbol used by Biek and others (2012)

40Ar/39Ar age is plateau age unless otherwise noted

age uncertainty = 2 standard deviations

Pre-1976 K-Ar ages corrected according to Dalrymple (1979)

* = low confidence

** = weighted mean age

*** = isochron age

NMGRL = New Mexico Geochronology Research Laboratory

NIGL = Nevada Isotope Geochronology Laboratory

AtoZ = Apatite to Zircon, Inc., Viola, ID

Whole rock means groundmass concentrate

Longitude and latitude of non-UGS samples may be slightly off due to projection uncertainties.

Table 3. Palynomorph Samples.

Sample Number	Longitude (W)	Latitude (N)	7.5' Quadrangle	Formation or Member	Map Unit Symbol	Identification	Notes
P062110-1	-112.86567	37.81505	Parowan	capping sandstone	Kwcs	Santonian to Campanian	about 75 feet above base
P062110-2	-112.86567	37.81505	Parowan	capping sandstone	Kwcs	Santonian to Campanian	1 foot below P062110-1
WP080410-1	-112.32274	37.68169	Wilson Peak	capping sandstone	Kwcs	Campanian	
PG110210-1	-112.94879	37.89765	Parowan Gap	Iron Springs	Ki	late Cenomanian to Turonian	about 20 feet below Kgc
WP080310-1	-112.36435	37.63129	Wilson Peak	John Henry	Ksj	Late Cretaceous, Santonian or older	UMNH Loc. 122
WP080310-3	-112.32817	37.6848	Wilson Peak	Kaiparowits, basal	Kk	late Campanian to Maastrichtian	about 30 feet above base of Kk
FA062210-1	-112.87973	37.65083	Flanigan Arch	Wahweap	Kw	Santonian to Campanian	about 150 feet below Kwcs
FA062210-2	-112.88001	37.64953	Flanigan Arch	Wahweap	Kw	Santonian to Campanian	about 250 feet below Kwcs
FA062210-3	-112.88001	37.64953	Flanigan Arch	Wahweap	Kw	Santonian to Campanian	about 30 feet below FA062210-2
TR070611-1	-112.2929	37.54985	Tropic Reservoir	Wahweap	Kw	Campanian to Maastrichtian	
WF070611-1	-112.88442	37.58065	Webster Flat	Wahweap	Kw	late Campanian to Maastrichtian	UMNH locality 11
WP070411-1	-112.30067	37.68045	Wilson Peak	Wahweap	Kw	Campanian to Maastrichtian	
WF062210-1	-112.89625	37.59367	Webster Flat	Wahweap, basal	Kw	Turonian to Coniacian	UMNH locality 10
TR070611-3	-112.34292	37.6084	Tropic Reservoir	Wahweap, upper	Kw	Late Cretaceous	just below Kwcs
WF062210-2	-112.88436	37.58061	Webster Flat	Wahweap, upper	Kw	Santonian to Campanian	UMNH locality 11
NL070611-1	-112.8675	37.5785	Navajo Lake	Wahweap, upper unit	Kwu	late Campanian to Maastrichtian	
TR070611-2	-112.3177	37.54273	Tropic Reservoir	Wahweap, upper unit	Kwu	late Campanian to Maastrichtian	
TR070611-4	-112.34495	37.60167	Tropic Reservoir	Wahweap, upper unit	Kwu	late Campanian to Maastrichtian	just above Kwcs
WP070611-1	-112.25888	37.69898	Wilson Peak	Wahweap, upper unit	Kwu	late Campanian to Maastrichtian	
WP080310-5	-112.32824	37.68433	Wilson Peak	Wahweap, upper unit	Kwu	Late Cretaceous	about 60 feet below base of Kk
WP080410-2	-112.32041	37.68291	Wilson Peak	Wahweap, upper unit	Kwu	Cretaceous	about 20 feet below Tcp cliff

Table 4. Wildcat exploration drill holes, all plugged and abandoned, in the Panguitch 30' x 60' quadrangle.

Map ID Number	API Well Number	Operator	Well Name	Year Abandoned	County	7.5' Quadrangle	Qtr/Qtr	Section	Township-Range	Ft. NS	NS	Ft. EW	EW	UTM Eastings	UTM Northings	Latitude	Longitude	TD
1	43-021-30009	DELTA PETROLEUM CORP	FEDERAL 23-44	2007	IRON	Parowan Gap	SESE	23	33S-10W	1062	S	1073	E	329132	4198227	37.91555	-112.94384	12094
2	43-021-10758	MOUNTAIN FUEL SUPPLY CO	LITTLE SALT LAKE GOVT 1 (WSW)	1963	IRON	Summit	NESE	9	34S-10W	2310	S	330	E	325975	4192037	37.8592	-112.97825	4400
3	43-021-30011	CEDAR MOUNTAIN GAS LLC	CLARK 1-28	2009	IRON	Webster Flat	SWNW	28	37S-10W	665	S	655	W	323920	4157241	37.54721	-112.99318	2017
4	43-017-30068	MAY PETROLEUM INC	PANGUITCH 1	1978	GARFIELD	Panguitch Lake	NESW	33	36S-7W	2546	S	2171	W	355193	4166654	37.63746	-112.64119	11610
5	43-017-10902	PHILLIPS PETROLEUM CO	HATCH FEE B-1	1963	GARFIELD	Asay Bench	SESE	2	37S-7W	820	S	549	E	359150	4164461	37.61832	-112.59593	4971
6	43-017-10901	PHILLIPS PETROLEUM CO	HATCH FEE A-1	1964	GARFIELD	Asay Bench	NESE	16	37S-6W	1980	S	660	E	365454	4161419	37.59185	-112.52397	4917
7	43-017-30106	NORTHWEST EXPLORATION CO	PANGUITCH 1	1981	GARFIELD	Panguitch	SWNW	7	35S-5W	2287	N	670	W	370747	4182717	37.78267	-112.46781	6752
8	43-017-30104	TEXAS INTERNATIONAL PETRO	DIXIE UNIT 1-19	1981	GARFIELD	Casto Canyon	NESW	19	34S-4.5W	1391	S	1910	W	380978	4188520	37.83635	-112.35261	14075
9	43-017-30115	ARCO OIL & GAS COMPANY	DIXIE UNIT 2	1982	GARFIELD	Blind Spring Mtn.	SWSW	2	33S-4.5W	960	S	1060	W	386527	4202827	37.96598	-112.29182	15251
10	43-017-30146	FELLOWS ENERGY LTD	10-33C2	2004	GARFIELD	Cow Creek	NWSE	33	33S-2W	1986	S	1782	E	411273	4194102	37.89011	-112.00907	1716
11	43-017-30112	SOUTH LOUISIANA PROD CO	CLAY CREEK FEDERAL 13-29	1982	GARFIELD	Flake Mtn. East	SWSW	29	34S-2W	660	S	660	W	408711	4185659	37.81377	-112.03714	12894
12	43-017-30084	CHAMPLIN PETROLEUM CO	CLAY CREEK FED 11-32	1982	GARFIELD	Flake Mtn. East	NWNW	32	34S-2W	660	N	661	W	408693	4185257	37.81014	-112.03729	8785
13	43-017-10375	FOREST OIL CORP	GOVT 1 (RED CANYON)	1959	GARFIELD	Wilson Peak	SENE	1	36S-4.5W	2970	S	990	E	387227	4173692	37.70353	-112.27931	6242
14	43-017-10662	LION OIL COMPANY	BRYCE-MONSANTO 1	1957	GARFIELD	Bryce Canyon	NWNW	10	36S-4W	990	N	990	W	392688	4172411	37.69264	-112.21718	11221
15	43-017-20350	BRYCE CANYON OIL CO	1	1928	GARFIELD	Tropic Canyon	NENE	36	36S-3W	2640	N	2640	E	406076	4165090	37.62998	-112.06441	400
16	43-017-30117	U R C CORPORATION	TROPIC STATE 1-29	1983	GARFIELD	Cannonville	NWNE	29	37S-2W	660	N	1980	E	409288	4157825	37.56299	-112.02712	6260
17	43-025-30009	TEXACO INC	GOVT SCHNEIDER A NCT-1	1971	KANE	Cannonville	SESW	5	38S-2W	1320	S	1320	W	408655	4153600	37.52485	-112.03376	5958
18	43-017-30126	ARCO OIL & GAS COMPANY	BUCK KNOLL U 1	1985	GARFIELD	Tropic Reservoir	SESW	36	37S-4.5W	880	S	1885	W	386488	4155281	37.53938	-112.28483	10119

Source: Utah Division of Oil, Gas, and Mining; http://oilgas.ogm.utah.gov/Data_Center/LiveData_Search/well_data_lookup.cfm; accessed March 13, 2012.

Note: Location of wells 9, 15, and 17 as reported above are slightly off true location, which is shown on plate 1.